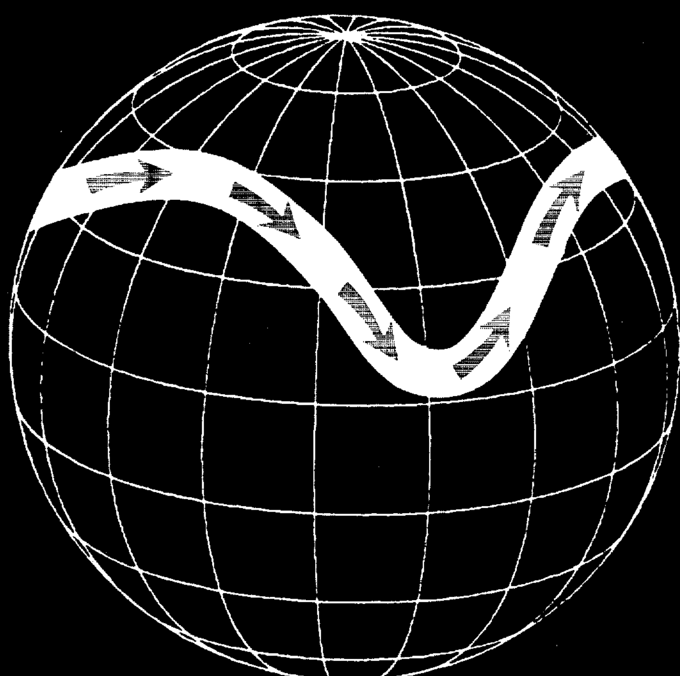
STC-2081
DECEMBER 15, 1985

REPORT OF THE NASA WORKSHOP ON
GLOBAL WIND MEASUREMENTS



REPORT OF A WORKSHOP
CONVENED IN COLUMBIA, MARYLAND
JULY 29–AUGUST 1, 1985

REPORT OF THE NASA WORKSHOP ON

GLOBAL WIND MEASUREMENTS

Report of the Workshop on
GLOBAL WIND MEASUREMENTS
Convened in Columbia, MD
July 29–August 1, 1985

Sponsored by the

NASA Global Scale Atmospheric Processes Research Program
under NASA Langley Research Center Contract No. NAS1-18057

Organized by

Science and Technology Corporation
P.O. Box 7390, Hampton, VA 23666-0321

REPORT OF THE NASA WORKSHOP ON
GLOBAL WIND MEASUREMENTS

Edited by

WAYMAN E. BAKER
NASA Goddard Space Flight Center
Greenbelt, MD

and

ROBERT J. CURRAN
NASA Headquarters
Washington, DC

A. DEEPAK PUBLISHING 1985
A Division of Science and Technology Corporation

Hampton, Virginia

CONTENTS

page

List of Tables ... *vii*
Organizing Committee ... *ix*
Preface ... *xi*

I. EXECUTIVE SUMMARY ... 1

II. WORKSHOP REPORT ... 5
1. INTRODUCTION ... 5

2. OBSERVATIONAL REQUIREMENTS FOR THE VARIOUS ATMOSPHERIC SCALES ... 7
2.1 Global and Synoptic Scale Requirements ... 7
2.2 Wind Data Required for Mesoscale Applications ... 9
2.3 Other Requirements for Wind Measurements ... 10
2.4 Recommendations ... 10

3. OBSERVING SYSTEM SIMULATION EXPERIMENTS ... 13
3.1 Background ... 13
3.2 Recent Simulation Studies ... 14
3.3 Recommendations ... 15

4. OPERATIONAL WIND SENSING TECHNIQUES ... 17
4.1 Balloon-based Systems ... 17
4.2 Cloud-motion Winds ... 18
4.3 Other Techniques ... 19

5. POTENTIAL SPACE-BORNE TECHNIQUES ... 21
5.1 Introduction ... 21
5.2 Instrument Description and Status and Areas of Application ... 21
5.2.1 Doppler Radar Winds ... 21
5.2.1.1 Microwave Systems ... 21
5.2.1.2 UHF/VHF Radar ... 21
5.2.1.3 Bistatic Systems ... 22
5.2.2 Scatterometer ... 22
5.2.3 Passive Triple-Etalon Fabry-Perot Interferometer ... 23
5.2.4 Electro-Optical Phase Modulation Correlation Wind Sensor ... 23
5.2.5 Enhanced Geosynchronous Satellite Wind Measurements ... 23
5.2.6 Lidar Systems ... 24
5.2.6.1 Aerosol Structure Correlation Technique ... 24
5.2.6.2 Incoherent Excimer Doppler Lidar Systems ... 24
5.2.6.3 Incoherent 0.5 μm Nd:YAG Doppler Lidar ... 24
5.2.6.4 Coherent 1.06 μm Nd:YAG Doppler Lidar ... 25
5.2.6.5 Coherent CO_2 Doppler Lidar ... 25
5.3 Resolution, Accuracy, and Coverage ... 26
5.4 Recommendations ... 27

PRECEDING PAGE BLANK NOT FILMED

6. ATMOSPHERIC AEROSOLS AND RELATED TRACERS 29
6.1 Background 29
6.2 Atmospheric Constituents Required for Lidar Measurements 29
6.2.1 Current Knowledge of Tropospheric Aerosols 29
6.2.2 Current Knowledge of Stratospheric Aerosols 30
6.3 Sampling Strategies and Error Analyses 31
6.3.1 Passive Doppler Interferometer/Spectrometer 31
6.3.2 Active Doppler Impediments 32
6.4 Currently Planned Efforts 33
6.5 Areas Requiring Further Study 34
6.6 Recommendations 35

7. AIR FORCE DEVELOPMENTS TOWARD SPACE WIND SENSING 37
7.1 Introduction 37
7.2 Currently Planned Efforts 38
7.3 Recommendations 38

8. RECOMMENDATIONS 41
8.1 Meteorological Uses of Wind Measurements 41
8.2 Wind Sensing Techniques 42
8.3 Atmospheric Aerosols 44

9. REFERENCES 47

APPENDIX A—TECHNICAL PROGRAM A-1
APPENDIX B—LIST OF PARTICIPANTS B-1
APPENDIX C—GLOSSARY OF ACRONYMS C-1

LIST OF TABLES

page

2.1 Root mean square values of satellite wind component error 8
2.2 Observational resolution required to nowcast or forecast various mesoscale phenomena 9
5.1 Expected resolution, measurement accuracy, and coverage of the various wind sensors 26

ORGANIZING COMMITTEE

Lt. Col. Charles P. Arnold, Jr.
United States Air Force

Dr. Robert M. Atlas
NASA Goddard Space Flight Center

Dr. Wayman E. Baker
NASA Goddard Space Flight Center

Mr. James Bilbro
NASA Marshall Space Flight Center

Lt. Col. John S. Bohlson
United States Air Force

Dr. Robert J. Curran
NASA Headquarters

Dr. Clifford H. Dey
NOAA National Meteorological Center

Maj. Gary Duke
United States Air Force

Dr. G. David Emmitt
Simpson Weather Associates, Inc.

Dr. George Fichtl
NASA Marshall Space Flight Center

Dr. Dan Fitzjarrald
NASA Marshall Space Flight Center

Dr. Freeman F. Hall
NOAA Wave Propagation Laboratory

Mr. R. Milton Huffaker
Coherent Technologies, Inc.

Dr. Eugenia Kalnay
NASA Goddard Space Flight Center

Dr. James B. Laudenslager
NASA Jet Propulsion Laboratory

Dr. M. Patrick McCormick
NASA Langley Research Center

Dr. S. H. Melfi
NASA Goddard Space Flight Center

Dr. Robert T. Menzies
NASA Jet Propulsion Laboratory

Dr. Joanne Simpson
NASA Goddard Space Flight Center

PREFACE

This report contains a summary of the discussions which took place during the Symposium and Workshop on Global Wind Measurements held 29 July–1 August 1985 at the Columbia Inn in Columbia, Maryland. The objectives and agenda for the Symposium and Workshop were decided during a planning meeting of the Organizing Committee (see page ix) held in Washington, DC, on 5 February 1985.

Invited papers were presented at the Symposium by meteorologists and leading experts in wind sensing technology from the United States and Europe. A special session was also held on the progress being made in wind sensing technology by the United States Air Force. The Workshop Participants were then divided into discussion groups in order to focus on key issues raised during the Symposium presentations. It is hoped that this Workshop Report will serve as a useful reference for the current research and development activities involving the meteorological uses of wind data and wind sensing technology and will contribute to the enhancement of our current wind observing capability.

The editors would like to acknowledge the excellent support and cooperation of the session chairmen and speakers which were essential to the success of the Symposium and Workshop. Many of the Workshop Participants who are listed in Appendix B contributed significantly to the writing of this Report. Their efforts are gratefully appreciated. Mr. James Bilbro, NASA Marshall Space Flight Center, Dr. Freeman Hall, NOAA Wave Propagation Laboratory, and Dr. Joanne Simpson, NASA Goddard Space Flight Center, contributed substantially to the organization of the Symposium sessions. Thanks are also due to Dr. John Theon, NASA Headquarters, for his helpful comments during the Workshop discussions. It is a pleasure to acknowledge the outstanding support provided by the Meetings Division staff of Science and Technology Corporation (STC), particularly the assistance of Carolyn Keen and Marilou Phillips with the Symposium and Workshop. Mary Goodwin and Diana McQuestion of the STC Publications Division did a superb job in typesetting and printing this Report. Mary Ann Wells and Donna Candido of M/A COM Sigma Data Incorporated patiently and expertly typed the many drafts of the Report.

Wayman E. Baker
Robert J. Curran

PART I. EXECUTIVE SUMMARY

Contained in this report is a summary of the discussions which took place during the Symposium and Workshop on Global Wind Measurements held 29 July–1 August 1985. The overall objectives of the Workshop were to:

1. Review the requirements for wind measurements for the various atmospheric scales;
2. Determine the capabilities and shortcomings of the current wind observing systems;
3. Critically appraise each potential new wind observing system; and
4. Establish requirements for future research and development.

Since a large majority of the work in this subject area takes place either in United States government laboratories or at universities and private industry supported through contracts from government agencies (NASA, NOAA, and DOD), the Workshop Organizing Committee included representatives from these respective areas. In order to meet the objectives listed above, meteorologists and leading experts in wind sensing technology from the United States and Europe were invited to present papers addressing:

1. The meteorological uses and requirements for wind measurements,
2. The various techniques for satellite remote sensing of wind and the latest developments in wind sensing technology, and
3. The status of our understanding of the atmospheric aerosol distribution (important for many wind sensing techniques).

A Proceedings of the Symposium containing a collection of the papers presented will be published separately.

Following the formal presentations, the Workshop Participants were divided into discussion groups to focus on key issues raised during the Symposium and work toward meeting the objectives of the Workshop listed above. Through the course of these discussions a consensus was reached on a set of recommendations which should help focus future research and development efforts toward the enhancement of our current wind observing capability. Only the recommendations having the highest priority for developing a spaceborne wind sensor will be mentioned in this summary. Other recommendations, equally important for the development of a comprehensive wind observing system and for improving the meteorological uses of wind data, are contained at the end of Sections 2 through 7. All of the recommendations are presented in Section 8.

Recent simulation studies have shown the importance of utilizing vertical profiles of wind data for numerical weather forecasting. The results indicate that useful forecast skill would be advanced by as much as 24 h in the southern hemisphere with wind profiles from a space-based lidar wind sensor. In addition, because wind profiles are primarily measured by land-based rawinsondes at the present time, the oceanic areas (covering roughly three quarters of the Earth's surface) and many regions of the less-developed southern hemisphere land areas are poorly observed. Therefore, *it is recommended that a space-based lidar wind sensor be developed in order to provide data for the investigation of atmospheric phenomena peculiar to these regions as well as data for global weather forecasting.*

Techniques identified for satellite measurements of wind profiles all utilize laser radar (lidar) transmitters. The transmitters operate in the visible and infrared portion of the spectrum, with the received signal due to backscattering from atmospheric aerosols. Because the speed of light is nearly constant (depending only on the index of refraction of the atmosphere), the time of flight of the laser pulse can be used to relate the received signal to the atmospheric altitude from which it is backscattered. The lidar techniques with the most extensive development compare the frequency of the received signal to that of the transmitter to determine the Doppler shift, and hence the radial velocity of the atmospheric aerosols relative to the lidar system. Suitable knowledge of the spacecraft velocity and multiple observations for the same location at differing azimuthal angles allow one to determine the wind vector.

Because the amount and variability of the atmospheric aerosol backscatter is a key factor in determining satellite laser power requirements and because little is known about the geographical or seasonal variability of the aerosol backscatter, *it is strongly recommended that an aerosol backscatter survey experiment be conducted.* This experiment would combine measurements of aerosol profiles from available ground-based lidar observatories as well as with data collected from a dedicated aircraft-based observing system. In addition, it is also recommended that data from previous and possibly continuing satellite experiments (e.g., SAM II, SAGE I, and SAGE II) be investigated for their potential in estimating aerosol backscatter variability.

A more complete understanding of the three-dimensional atmospheric wind field is not only essential for improved global weather forecasting, it is also important for the investigation of the complex interactions between the atmosphere, the biosphere, and the hydrosphere. There is agreement within the scientific community that one of the key ingredients needed for making significant progress in addressing the myriad of multidisciplinary questions confronting the Earth sciences is in our ability to treat the Earth as an integrated system composed of interactions among the various subsystems (atmosphere, biosphere, and hydrosphere). In order to accomplish this, observational capabilities must be developed to collect data from the small scales up to those which can be measured by a satellite-based observing system.

For the satellite-based segment of the total observing system, a number of polar orbiting satellites are being considered as part of an Earth Observing System (Eos) mission. Eos would be an ideal mission in which the Doppler lidar wind profiler could participate because of the synergism it will provide among the many types of instruments. In addition, the Doppler lidar system presently envisioned has physical requirements compatible with the capabilities of the Eos platform. Therefore, *it is recommended that the Doppler lidar wind profiler be considered for participation in Eos.*

The Doppler lidar with the most extensive background in terms of ground-based and airborne applications and testing is the CO_2 coherent Doppler lidar. Even though this system has an impressive heritage, a number of technological issues remain to be addressed before it can be considered for a year or more of autonomous operation on a polar orbiting platform including: (1) the demonstration of a laser with adequate power and suitable spectral coherence in a space environment, and (2) the demonstration of reasonable laser lifetime at the power levels required. A useful step toward the implementation of a Doppler lidar wind profiler on a polar orbiting platform would be its participation in a lower altitude Shuttle mission of one to two weeks duration, such as that proposed for the Shuttle Coherent Atmospheric Lidar Experiment (SCALE) discussed in Section 5.2.6.5. Besides demonstrating the wind sensing capability of the Doppler lidar at the lower power levels commensurate with the lower Shuttle altitude, a number of interesting scientific questions could be pursued with such a mission. Consequently, *it is recommended that serious consideration be given to conducting a coherent CO_2 Doppler lidar experiment on the Shuttle.*

In conclusion, in this brief summary and the Workshop Report that follows, the scientific justification and rationale for obtaining satellite-based wind profiles are presented. A variety of different wind sensing techniques are discussed as well as the remaining technological issues which need to be addressed before operational deployment in space can be achieved. The Earth Observing System is identified as the most promising platform from which a wind sensing system could provide the greatest scientific return. Finally, the steps to be taken to achieve this capability in space are discussed.

PART II. WORKSHOP REPORT

SECTION 1

INTRODUCTION

The Symposium and Workshop on Global Wind Measurements, sponsored by the NASA Global Scale Atmospheric Processes Research Program, was held 29 July–1 August 1985 at the Columbia Inn in Columbia, Maryland. Invited papers were presented at the Symposium (Appendix A contains the technical program) by meteorologists and leading experts in wind sensing technology from the United States and Europe on: (1) the meteorological uses and requirements for wind measurements, (2) the latest developments in wind sensing technology, and (3) the status of our understanding of the atmospheric aerosol distribution. A special session was also held on the latest developments in wind sensing technology by the United States Air Force.

The Workshop participants (Appendix B) were divided into discussion groups in order to focus on key issues raised during the Symposium presentations (a Proceedings containing a collection of the papers presented at the Symposium will be published separately) and to: (1) review the requirements for wind measurements for the various atmospheric scales, (2) determine the capabilities and shortcomings of the current wind observing systems, (3) critically appraise each potential new wind observing system, and (4) establish requirements for future research and development. The consensus of the Workshop was that the measurement of tropospheric wind profiles over data-sparse regions would significantly improve numerical weather forecasts, that it is now technologically feasible to measure winds from space, and that a vigorous program should be pursued to assess the geographical distribution of atmospheric aerosols, a critical issue for a spaceborne wind observing system. This report attempts to summarize the conclusions from the Workshop discussions and present recommendations for achieving the long-term goal of constructing a spaceborne wind-sensing system as part of the Earth Observing System (Eos) in the 1990s. In Section 2, the observational requirements for wind measurements are provided. The results of some observing system simulation experiments are presented in Section 3. The wind sensing techniques which are already operational are discussed in Section 4, and the various potential spaceborne techniques are reviewed in Section 5. Section 6 presents the status of our understanding of atmospheric aerosols, and recent developments toward space wind sensing by the United States Air Force are contained in Section 7. Finally, the recommendations of the Workshop are summarized in Section 8, and references are provided in Section 9.

SECTION 2

OBSERVATIONAL REQUIREMENTS FOR THE VARIOUS ATMOSPHERIC SCALES

There is a wide variety of requirements for wind measurements at the different atmospheric scales. Wind observations are needed for both operational as well as research purposes. This section will concentrate primarily on the requirements for wind measurements for numerical weather (or atmospheric) analysis and prediction, but other needs will also be addressed.

2.1 GLOBAL AND SYNOPTIC SCALE REQUIREMENTS

One of the most important applications of wind observations is the field of numerical weather prediction (NWP). Significant progress has been made in this area in the last ten years, especially with the development of accurate global numerical weather prediction models, as well as with improved global coverage of the atmosphere provided by satellite observing systems. With the successful completion of the Global Weather Experiment in 1979, operational centers [e.g., European Centre for Medium Range Weather Forecasts (ECMWF), National Meteorological Center (NMC)] and research laboratories [e.g., Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Laboratory for Atmospheres (GLA)] began producing forecasts that retained some useful skill beyond five days, much longer than was possible just a few years before. However, we are still not close to the two-week theoretical limit of dynamical predictability, and it is clear that further improvements will be necessary both in the observations that provide the initial data for the models as well as in the objective analysis techniques and in the models themselves.

The first numerical weather prediction models were designed to use *only* mass (pressure and temperature) data. Winds were derived from the mass observations using the geostrophic relationship. This relationship assumes that the latitudinally dependent Coriolis force is balanced by the pressure gradient force. This was a natural choice because pressure observations were more abundant and more accurate than wind observations. Recently, however, it has become increasingly clear that wind data are extremely effective for use in numerical weather prediction. There are two independent reasons for this (Kalnay *et al.*, 1985). The first reason derives from the concept of geostrophic adjustment (Rossby, 1938; Washington, 1964; Daley, 1980). For most of the scales of importance to numerical weather prediction, the models effectively retain wind data incorporated into the initial conditions. Pressure or height data are not retained as well unless they are forced *a priori* to be in geostrophic balance with the winds. Simply posed, for most of the scales important to NWP, models accept the wind data more readily than the mass data.

The second reason why winds are an extremely effective source of data comes from the well-known fact that integration of noisy data reduces the effect of random noise, whereas differentiation enhances the effect of noise. The geostrophic relationship implies that wind is proportional to the horizontal pressure gradient, so that winds become an increasingly more accurate measure of the atmospheric state than pressure or height measurements for increasingly smaller scales. Specifically, winds are relatively more accurate than height measurements if $\delta v < (2\pi g/Lf_o)/\delta z$, where δv and δz are the wind and height errors respectively, L the horizontal scale, g gravitational acceleration, and f_o the average value of the Coriolis parameter. As pointed out by Phillips (1983), this relationship indicates that for short scales

($L \sim 2000$ km), satellite winds with a component accuracy of 2.7 m s^{-1} at 500 mb and 5.0 m s^{-1} at 250 mb would bring the combined accuracy of satellite temperature and winds to the same level globally that the current rawinsonde network has over land in the northern hemisphere (see Table 2.1 below).

TABLE 2.1. Root-mean-square values (m s^{-1}) of satellite wind component error (as a function of horizontal scale) that will, in combination with satellite temperature data, produce midlatitude analyses over the ocean as accurate as the conventional rawinsonde system does over continents. The figures should be multipled by $\sqrt{2}$ to give rms vector wind errors. Reproduced from Table 2 of Phillips (1983).

Horizontal Scale	Pressure level	
L(10^6 m)	500 mb	250 mb
2	2.7	5.0
4	1.8	3.7
6	1.2	2.8
8	1.0	2.2

As pointed out by R. Rosen (personal communication, 1985), a measure of the accuracy of current operational wind analyses can be obtained by comparing the differences between NMC and ECMWF time series of the atmosphere's angular momentum, which is proportional to the zonally averaged zonal wind field. When separated into latitude belts, the NMC-ECMWF differences demonstrate their sensitivity to the current distribution of wind observations. Thus, these differences are vanishingly small in northern hemisphere middle and high latitudes, but are significant within the tropics and southern hemisphere extratropics. This latter result provides an interesting insight into the relative importance of mass and wind data outside the tropics, for although temperatures in the midlatitudes of the southern hemisphere are provided by satellite retrievals, these do not appear to be adequate enough to compensate for the lack of wind data there.

In the tropics, wind observations are even more important for numerical weather prediction since the quasi-geostrophic balance, present in the midlatitudes, breaks down. As a result, the wind field cannot be determined from the height field. Moreover, a reliable estimate of the divergent component of the wind is necessary to depict the convective areas in the tropics which provide a source of energy for not only the equatorial regions but also at times the midlatitudes. Recently, Krishnamurti *et al.* (1984) have found that tropical divergent and non-divergent circulations display interesting contrasts between El Niño and non-El Niño years. A number of other anomalous circulations are also apparent in the tropical wind field.

The problem of data assimilation in the tropics is particularly serious because of the lack of wind profiles throughout the troposphere. Single-level reports, such as from cloud-track winds, are inadequate to capture the detailed vertical structure of the tropical atmosphere (also a problem in the midlatitudes). This may explain why in some cases the tropical wind data which existed during FGGE[1] (primarily cloud-track wind data) exerted a negative influence on the extratropical forecasts (Baker and Paegle, 1983; Kalnay *et al.*, 1985). The impact of the cloud-track wind data would undoubtedly be more positive if the quality is improved. Also, wind profiles are needed to reduce the rapid model error growth in the tropics resulting from deficiencies in parameterizing convective activity.

[1]First GARP (Global Atmospheric Research Program) Global Experiment

2.2 WIND DATA REQUIRED FOR MESOSCALE APPLICATIONS

Along with the increasing recognition of the importance of having global measurements for successful medium range (3–10 days) and short range (1–2 days) numerical weather forecasts, the importance of obtaining mesoscale and cloud-scale observations for very short term (3–18 h) forecasts and nowcasts (0–3 h) is also becoming increasingly evident. For example, there is more and more evidence that many of the most significant cool and warm season weather events are strongly impacted by jet streaks and their associated secondary (vertical) circulations (e.g., Cahir, 1971; Brill *et al.*, 1985). The conventional sounding network has difficulty resolving these mesoscale features and, as a consequence, the initial conditions for operational numerical models fail to capture important details necessary for a successful forecast. Obtaining the necessary mesoscale information to make such predictions is particularly important in this case since mesoscale convective systems are responsible for much of the severe weather and many flash floods now the leading meteorological cause of fatalities and property damage in the United States. On even smaller scales (e.g., cloud-scale circulations), it is now well documented that high-resolution (in both time and space) observations of boundary layer winds are necessary to nowcast the disastrous low-level wind-shear conditions (microburst) that frequently plague the aviation industry during takeoffs and landings (Roberts and McCarthy, 1985). Morever, numerical experiments with three-dimensional thunderstorm models have shown how knowledge of the local wind hodograph is one of the key factors in determining whether or not a severe thunderstorm becomes tornadic. Neither the high resolution boundary layer winds nor the local wind hodographs are routinely available for operational use. Thus, it is evident that, from global scale atmospheric phenomena down to individual cloud circulations, there is a strong need for additional wind measurements.

The observational resolution generally required to nowcast or forecast various mesoscale phenomena, which is addressed in a variety of documents (e.g., Federal Coordinator for Meteorological Services and Supporting Research, 1982; The National STORM[2] Program, 1984; Shenk *et al.*, 1985; National Environmental Satellite, Data, and Information Service, 1985), is contained in Table 2.2. The scale subdivision generally follows that suggested by Orlanski (1975) for the meso-α and meso-β phenomena. The last column in Table 2.2 might be

TABLE 2.2. Observational resolution required to nowcast or forecast various atmospheric phenomena.

	Characteristic resolution		
	meso-α[1]	meso-β[2]	meso-γ[3]
Horizontal	100 km	10 km	0.1 km
Vertical	25 mb	10 mb	10 mb
Temporal	1 h	10 min	1 min

[1] The initiation of a mesoscale convective system (MCS) (The National STORM Program, 1984), for example.
[2] Quantitative description of the internal structure of the MCS (The National STORM Program, 1984), for example.
[3] Low-level wind-shear (microburst), for example.

[2] STormscale Operational and Research Meteorology

better referred to as microscale. However, the majority of requirements addressed in this report best fit into the global and synoptic scale and mesoscale categories. The observational requirements listed for the microburst problem, for example, are therefore denoted as meso-γ requirements because most of the microscale requirements are not addressed in this report. It would seem from Table 2.2 that satellite-based remote sensing platforms, because of their orbital constraints, would be most helpful in meeting the observational requirements at the meso-α scale. For the meso-β and meso-γ phenomena, ground-based systems such as the Doppler radar wind profilers (Schlatter, 1985) would seem to be the most useful. However, in some situations geosynchronous cloud-motion winds could be useful for meso-β events.

2.3 OTHER REQUIREMENTS FOR WIND MEASUREMENTS

In addition to the fundamental meteorological requirements for wind measurements, there are vital needs for wind measurements in direct support of both civilian and military activities. Typically, operational data requirements are described in terms relevant to the operational decision to which the data will be applied. Some examples of these applications would be: when to launch a space vehicle, which aircraft or ship route to follow in order to minimize fuel consumption, where and how to move people and equipment, whether to evacuate or seek shelter in advance of severe weather. For the decision of whether or not to launch a space vehicle, for example, critical values of wind shear or turbulence must be determined along the flight path. A horizontal resolution of less than 1 km, vertical resolution on the order of tens of meters, and accuracies on the order of 1 to 2 m s^{-1} are desirable.

Accurate, global measurements of wind data would also be helpful in a variety of diagnostic investigations such as in studies of the transport of water vapor, ozone, and other atmospheric constituents. Also, as pointed out by R. Rosen (personal communication, 1985), the geodynamics community would benefit from accurate, global wind measurements as well. Recent studies of the angular momentum balance of the earth-atmosphere system reveal that current geodetic and atmospheric data sets are capable of detecting day-to-day changes in this balance to very good precision. The geodetic measurements of changes in the solid earth's angular momentum, reckoned in terms of changes in the length of day, are derived from a variety of space-based techniques that are expected to become significantly more accurate in the next several years. On the one hand, this means that the geodynamics community will desire increasingly more accurate analyses of the atmosphere's angular momentum. On the other hand, high precision earth rotation data have the potential of providing an important global constraint on analyzed variations in the zonal wind field.

2.4 RECOMMENDATIONS

From the material presented above, it is recommended that for the *global and synoptic scales:*

1. The coverage of the present global operational observing system for measuring winds should be increased over the oceans and in the tropics and the southern hemisphere.
2. The spatial and temporal resolution should be compatible with the resolution of the present and future numerical prediction models. A horizontal resolution of about 100 km, vertical resolution of about 1 km ($\sim$ 0.5 km in the boundary layer and vicinity of the jet stream), and temporal resolution of 6 h are needed.

3. The accuracy of the horizontal wind components should be on the order of 1 to 2 m s^{-1} in the lower troposphere and 2 to 5 m s^{-1} in the upper troposphere, in order to make the observing system over the oceans as useful as the rawinsonde network over land.
4. Wind profiles rather than single-level data should be measured for use in numerical analysis and forecasting because the profile data can be utilized more effectively. Recent simulation studies (see Section 3) also indicate that more accurate forecasts would result from using additional wind profiles compared to those obtained with additional single-level winds.

For the mesoscale, it is recommended that:

5. Satellite-borne remote sensing platforms should be used to obtain 100 km (meso-α) horizontal resolution soundings of wind, temperature and moisture coincident in time and space. For temperature and moisture, satellite-based platforms should be used to obtain $\sim$10 km resolution soundings for a variety of mesoscale events (meso-α down to meso-β).
6. Accuracies should be on the order of 1 m s^{-1} for the horizontal wind components and 1 K for temperature and dew point.
7. Ground-based systems should be used to fulfill high-resolution observational requirements for meso-β and meso-γ phenomena (see Table 2.2) for those requirements which cannot be met with space-based systems.

SECTION 3

OBSERVING SYSTEM SIMULATION EXPERIMENTS

3.1 BACKGROUND

In recent years a number of advanced observing systems have been proposed to provide improved initial conditions for global numerical weather prediction and improved analyses for atmospheric circulation dynamics studies. Observing system simulation experiments (OSSEs) provide a means to evaluate the potential improvement in analysis and forecast accuracy to be gained from different observing systems as well as the relative importance of different types of observations. Such studies can also assist in the design and implementation of specific observing systems.

The concept of an observing system simulation experiment was apparently first conceived by Newton (1954), who suggested that fictitious (simulated) observations could be used to evaluate the effect of variations of the observational network on numerical forecasts. Several investigations followed—Best (1955), Bristor (1958), and Jess (1959). Bristor's work is of particular interest, because it was the first known actual OSSE. In his experiment, Bristor created simulated observations from a hypothetically correct actual analysis (the reference atmosphere), and examined the effect of network density and observational error on both analyses made with the simulated data and the ensuing numerical predictions. However, neither fundamental alterations of nor significant additions to the observational network in which OSSEs could play a role were taken into consideration at that time, so interest in these experiments waned.

With the exception of an interesting theoretical paper by Alaka and Lewis (1967), the hiatus of activity in this area continued through almost all of the 1960s and the OSSE remained a solution looking for a problem. However, motivation for renewed interest was provided by the initiation of the Global Atmospheric Research Program (GARP) in 1967. One of the stated objectives of GARP was to determine acceptable compromise solutions to the data requirement problem. In order to meet this objective, the U.S. Committee for GARP proposed a national effort to study the predictive consequences of proposed observation systems known as "Observing System Simulation Experiments" or OSSEs. A landmark paper by Charney *et al.* (1969) ushered in the period of intense activity with OSSEs. Their approach was to use a model forecast to provide a four-dimensional reference atmosphere. Starting from a perturbed initial state, a second forecast was then made with the same prediction model (the assimilation run). Simulated observations taken from the reference atmosphere were inserted into the assimilation run, and the degree to which the assimilation run approached the reference atmosphere was examined. Because the same numerical prediction model that was used to generate the reference atmosphere was also used to make the assimilation run, this type of experiment is referred to as an identical twin experiment. A number of identical twin experiments followed, for example: Halem and Jastrow (1970), Jastrow and Halem (1970), Williamson and Kasahara (1971), Bengtsson and Gustavsson (1971), Kasahara and Williamson (1972), and Gordon *et al.* (1972).

Williamson and Kasahara's 1971 paper was the first to question the use of identical twin experiments. They proposed instead an alternative which is referred to as the fraternal twin experiment. In this approach, the numerical prediction model used for the assimilation had lower resolution and less sophisticated physics than the model used to generate the reference atmosphere. It soon became apparent that identical twin experiments gave unrealistically optimistic results, and the fraternal twin approach gained favor. By 1974, the Joint Organizing Committee for GARP specifically ruled out the use of identical twin experiments to determine which of the possible special observing networks would be most effective during GARP. A number of fraternal twin experiments were run, notably those of Williamson (1973), Lorenc (1975), and Bromley (1978).

With the advent of satellite temperature profiles, the lack of wind profiles on a global scale has been viewed as perhaps the major deficiency in our observational network. By the end of the 1970s, technical developments suggested that active laser radar (lidar) methods might be able to fill this need (Huffaker, 1978; Huffaker *et al.,* 1980). By mid-1980, the Defense Meteorological Satellite Program was considering such an approach, and supported a feasibility study by NOAA's Wave Propagation Laboratory (WPL). It was concluded from the feasibility study that the idea had merit, but that it was likely to be expensive. This led to the recommendation that, among other things, the benefits such data might be expected to produce be thoroughly examined through OSSEs.

3.2 RECENT SIMULATION STUDIES

A workshop was held at NMC in February 1983 to plan a more realistic experimental design. Following the workshop, a series of simulation studies was conducted as a cooperative effort among ECMWF, NMC, and GLA to provide a quantitative assessment of the potential impact of future observing systems on large scale numerical weather prediction. The methodology and results from these experiments are described by Atlas *et al.* (1985), Dey *et al.* (1985), and Arnold *et al.* (1985). A general conclusion from the analysis/forecast experiments performed at GLA and NMC is that the use of wind profile data produces more accurate analyses and 1-5 day forecasts than temperature data or single-level wind data, and advances the useful skill by as much as 24 h in the southern hemisphere.

Experiments are currently underway at GLA to simulate more realistic observations. The quantitative effect of wind profile data in the northern hemisphere will then be evaluated. Experiments are also planned to evaluate alternative wind profile measurements.

At ECMWF and most of the European weather services, the simulation efforts are concentrated on network studies for the future North Atlantic network in relation to the Operational WWW (World Weather Watch) System Evaluation (OWSE), which is to take place in 1987–88. During and immediately after the OWSE for the North Atlantic, efforts will concentrate on quasi real-time evaluations of the systems deployed over the Atlantic Ocean.

The National Center for Atmospheric Research (NCAR) plans to conduct more OSSEs for the ground-based wind profilers. The emphasis is on the optimum network design for the 30 profilers to be deployed by NOAA/WPL in the near future. In the long term (> 3 years), NCAR plans to conduct OSSEs for the design of the next generation observing network employing a combination of profilers, rawinsondes, NEXRAD (Next-Generation Weather Radar), satellite, and surface measurements.

The capability of performing OSSEs has also been developed at the Air Force Geophysics Laboratory (AFGL) in recent years. A global spectral model of variable resolution has been developed based on the 1980 version of the NMC global spectral model. A data assimilation scheme has also been constructed based on the Bergman (1979) version of the OI (optimum interpolation) procedure.

For mesoscale OSSEs the problem is even more complex and is at a much earlier stage of development. The difficulties in conducting mesoscale OSSEs lie mainly in the accurate simulation and verification of mesoscale circulations. Obtaining a realistic mesoscale simulation is considerably more difficult than a synoptic-scale simulation. The major reason is that a mesoscale simulation is more sensitive to physical parameterizations (such as cumulus parameterization). Another problem is that routine measurements do not allow adequate verification for mesoscale simulation.

It is also apparent that the classical skill scores (i.e., rms and S_1) used to evaluate synoptic-scale OSSEs are not suitable for mesoscale OSSEs. For instance, one might get an rms error of 1 K for temperature retrievals (Kuo and Anthes, 1985) for one OSSE experiment, which does not look significant from a synoptic point of view. However, there may be local errors as large as 5 °C. This would completely change the static stability and give a different prediction for a subsequent forecast.

3.3 RECOMMENDATIONS

Further work is needed to increase the realism of simulating the future global observing system, refine data requirements, determine the effect of improved utilization of current and advanced temperature sounders in relation to a wind profiler, and evaluate the effect of more realistic wind profile observations. This includes the effect of correlated errors, coverage, resolution and accuracy.

In addition, OSSEs are needed to quantitatively assess the potential usefulness of proposed observing systems for global and mesoscale numerical weather prediction, local weather forecasting and diagnostic studies of atmospheric phenomena on a variety of scales. The OSSEs, conducted to date, indicate a very significant potential for a space-based wind profiler system. However, these studies should be expanded in a number of ways.

Up to now, the OSSEs concerned with wind measurements have been carried out on the tacit assumption that the wind observations available to the analysis/forecast model are colocated both spatially and temporally with the temperature and humidity observations on TIROS-N. It is likely that different measurement systems may provide wind data in a manner and mode quite different from this and therefore produce different scenarios for which different OSSEs would have to be designed. Closer attention should also be given to the sampling and measuring characteristics of the observing systems under study in order to best incorporate them into the design of OSSEs. Coordination between general circulation model (GCM) users and satellite Doppler wind profiler developers should be undertaken to improve satellite wind profiler simulations by including in the simulation experiments:

1. A statistical parameterization of the scanning errors based on mesoscale simulations, and
2. A statistical parameterization of the global aerosol distribution to account for its effect on the Doppler lidar signal to noise ratio and associated wind field errors.

The errors in items 1 and 2 above should be imposed in a systematic way so that the individual and combined effects of these errors along with cloud distribution effects can be understood in terms of potential impact on the diagnosis and prediction of the atmosphere.

It is also recommended that:

3. An additional model integration ("nature") be generated by ECMWF, which would provide an additional record of the "true" state of the atmosphere, in order to in-

crease the sample size for the OSSEs. Analysis/forecast experiments should also be conducted using more than one model if possible.

Further consideration should also be given to the measures of performance or impact in representing the results of any OSSE using global models. In addition to using an rms or S_1 score, measures that are more appropriate in characterizing other attributes of performance of the model should be used. For example, one might use the deviations in distance of storm tracks or of jet streams, or the deviations in intensity or position of high or low pressure systems (e.g., see Williamson, 1981).

For the mesoscale, physical parameterizations and objective analysis and initialization methods must continue to be improved. A considerable research effort is required to develop mesoscale simulation methodology. Following the development of such methodology the effect of alternative wind observing systems should be evaluated. The assessment should include stability indices and precipitation.

SECTION 4

OPERATIONAL WIND SENSING TECHNIQUES

The emphasis on mesoscale research over the next decade (GALE[1], MIST[2], SPACE[3] STORM) is pushing the development and deployment of observing systems to obtain improved measurements of winds on the regional scale including:

Portable Automated Mesonet (PAM)—surface
Profiler—0.5 to 15 km altitude
Cross-Chain Loran Atmospheric Sounding System (CLASS)—0 to 20 km altitude
Aircraft dropwindsonde—0 to 12 km altitude
Doppler Radar—cloud winds and meso-γ phenomena

During the STORM program extremely useful regional data sets will be accumulated with these systems. These should serve as test sets for calibration of winds derived from cloud-motions and other satellite-based measurement systems. The potential suggested by recent studies for deriving the temperature field from a dense network of profiler measurements of winds (e.g., Kuo and Anthes, 1985) should be vigorously explored.

4.1 BALLOON-BASED SYSTEMS

In data-sparse regions there is a need for "ground" reference. The MICRO-GHOST[4] system (Lally, 1985) can provide such a reference and benchmark level at 200 mb in the southern hemisphere. This capability would be most useful to calibrate lidar measurements from the Shuttle, UARS (Upper Atmosphere Research Satellite), and other platforms for special observing periods. It can also serve as a means of enhancement of radiometer-derived winds from operational polar-orbiters.

In addition to the reference-level winds from balloon platforms, the balloon-borne triple-etalon Fabry-Perot interferometer (Rees, 1985) may be used to measure winds in the upper troposphere and lower stratosphere. The interferometric data can provide wind measurements over a height range from 5 to 50 km in regions of clear air with a resolution of 4 km. The technique is a potentially valuable complement to existing wind measuring systems and can provide a low-cost addition to the powerful active wind-measuring systems now under development. The technique relies on the generation of narrow absorption lines by major atmospheric species such as O_2 and H_2O. Molecular oxygen is particularly useful for providing wind profiles at any location for the daytime hemisphere. However, in the upper troposphere and lower stratosphere, water vapor provides a means of obtaining higher vertical resolution (about 2 km), when it is present in adequate concentrations. It should be noted that this technique is the demonstration of the High Resolution Doppler Imager (HRDI) to be used on UARS (see Section 5.2.3) with the same overall capabilities and limitations.

---

[1] Genesis of Atlantic Lows Experiment
[2] Microburst, Severe Thunderstorms
[3] Satellite Precipitation and Cloud Experiment
[4] Operational Successor to the GHOST (Global HOrizontal Sounding Techniques) system.

4.2 CLOUD-MOTION WINDS

Cloud-motion winds (CMWs), now part of the operational observation system, have been available since the launch of the Applications Technology Satellite (ATS-1) spin scan camera in 1966. During the 1979 FGGE year, the number of cloud motion winds increased significantly (e.g., Fleming *et al.,* 1979a,b; Halem *et al.,* 1982). Mesoscale analyses with CMWs have shown how they contribute to defining the lower tropospheric convergence field ahead of the development of severe convection (Negri and Vonder Haar, 1980; Maddox *et al.,* 1977; Peslen, 1980; and Peslen *et al.,* 1985). Aircraft verifications of cloud motion-wind relationships (e.g., Hasler *et al.,* 1979) have shown that cumuliform clouds over water move within 1.5 m sec^{-1} of the winds at the cloud base with no apparent bias. Cirrus clouds were found to move within 2–3 m sec^{-1} of the wind in relatively low ($\sim$ 15 m sec^{-1}) wind speed situations. These aircraft results suggest that there is potential for the satellite wind measuring system and wind extraction procedures to be improved significantly beyond the current operational accuracies of 4 m sec^{-1} for cumuliform clouds and 8 to 10 m sec^{-1} for cirrus. Deficiencies in the cloud-tracking techniques (e.g., level assignment) may have contributed to the negative impacts found in some cases in the analyses and subsequent forecasts in which the data have been used (e.g., Ebersole, 1984; Kallberg *et al.,* 1985; Kalnay *et al.,* 1985).

Suggestions for the improvement of the quality and coverage of the CMWs as well as their utilization follow.

1. The height measurement of clouds could be improved by:
   - (a) Implementing stereo cloud-top height (and perhaps cloud-base) determination via simultaneous imagery from two geosynchronous satellites.
   - (b) Implementing multispectral infrared techniques from VAS data to measure cloud-top heights.
   - (c) Increasing the utilization of surface data and thermodynamic calculations to estimate cloud-base heights in the lower troposphere.
2. Provide sufficiently high frequency geosynchronous satellite imagery (e.g., 3 min image interval) to calculate mesoscale wind fields several times a day.
3. Continue to use CMWs in tropical/subtropical environments. However, when the cloud height uncertainty is greater than 50 mb, then the vertical wind shear should be required to be less than $\sim$ 4 m s^{-1} km^{-1} for suitable wind accuracy to be achieved. Also, the cloud emissivities should be high enough that height uncertainties do not introduce unacceptable errors. The use of the estimated shear ($\partial v/\partial z$) could also be initiated, in conjunction with estimates of height measurement errors (Δz_ε), to assign expected error bounds to CMW data in operational settings [i.e., $\Delta v_\varepsilon=(\partial v/\partial z)\ \Delta z_\varepsilon$].
4. Conduct *in situ* verification of CMW estimates to determine actual representativeness of these estimates in vertically sheared situations. Measurements made from ground-based wind profilers and aircraft equipped with inertial navigation systems, such as those which could become available in upcoming mesoscale experiments like GALE and STORM, could be used for these purposes. There is also a great potential for the use of satellite lidar data in such verification studies. There is a critical need to know whether low cloud-base levels over land are the most representative levels for CMW level assignment, and what cloud sizes and types are the best tracers of air motion.
5. Once the CMW heights are determined, the entire set of vectors must still be assigned to a coordinate surface before the data can be utilized in either diagnostic studies or

for model initialization. Even if heights could be perfectly measured, the assignment step could still introduce significant errors > 5 m s^{-1}. This problem could be alleviated by the following:

(a) A priori knowledge of the vertical wind shear profile (either from a mesoscale model forecast or some instrument like the profiler) should improve the accuracy of the interpolation of the CMWs from their actual levels to the coordinate surface.

(b) In the absence of (a), an arbitrary assignment of CMWs to a sigma (σ) surface should reduce the magnitude of the vector differences between combined (rawinsonde and CMW) winds and rawinsonde winds (Peslen *et al.*, 1985), unless a moisture discontinuity is crossed, in which case,

(c) The use of multiple σ surfaces representative of the different air masses is also recommended by Peslen *et al.* (1985).

In order to develop a capability to properly utilize CMW mesoscale fields, major operational centers like NMC, NSSFC,[5] and PROFS[6] should be encouraged to participate in addressing the following topics:

6. Objective analysis techniques should be tailored to the specific characteristics of CMW data, namely, their highly non-uniform coverage and their (presently inadequately understood) unique statistical structure. Existing CMW data sets are adequate for this research, particularly those collected in SESAME (Severe Environmental Storms and Mesoscale Experiment).

7. Mesoscale model sensitivity studies need to be conducted to determine the utility of cloud-motion wind data, since such data have not yet been shown to produce consistent impacts in model forecasts.

8. Techniques need to be developed to allow CMW data to be merged or synthesized with other mesoscale data such as from PAM, wind profilers, Doppler lidar, etc.

4.3 OTHER TECHNIQUES

The World Meteorological Organization initiatives in expanding shipboard soundings ASAP (Automatic Shipboard Aerological Program) and flight-level winds from wide-bodied jets ASDAR (Aircraft to Satellite Data Relay) will provide a much needed expansion of wind measurements over the oceans until the advent of an operational satellite wind program. However, the coverage by ASDAR and ASAP will be incomplete in both space and time.

Further research is encouraged on the water vapor wind determination method (Stewart and Hayden, 1985). In that regard, a more objective determination of water vapor signatures used for tracking is required. The question of what should be the proper height assignment in remote areas (away from other temperature and moisture data sources) should be addressed because temperature and moisture influence the results. Also, the comparison with other data should include layer-averaged winds since the 6.7 μm channel represents a 200–300 mb thick layer.

---

[5] National Severe Storms Forecast Center

[6] Program for Regional Observing and Forecasting Services

Gradient winds from gridded analyses of TOVS (TIROS-N Operational Vertical Sounder) temperature soundings may provide information in the absence of other data (conventional or cloud-drift). Because the error levels for the gradient winds are comparable with those for the NESDIS (National Environmental Satellite, Data, and Information Service) and European cloud-drift winds (J. Ward, personal communication, 1985), they could be used to evaluate other methods in cloud-free areas (i.e., water vapor winds), where the gradient wind approximation is valid.

SECTION 5

POTENTIAL SPACEBORNE TECHNIQUES

5.1 INTRODUCTION

The purpose of this section is to discuss the current remote sensing technology for obtaining global wind profiles from a space platform. Many sensors have been proven for ground or aircraft wind measurements and these should now be reviewed vis-a-vis the feasibility of measuring winds from a space-based system. Consequently, each instrument is reviewed in terms of: (1) the possible areas of application, (2) the present status in the development of the technique and the hardwave components, and (3) the expected resolution (horizontal, vertical, and temporal), measurement accuracy, and coverage.

5.2 INSTRUMENT DESCRIPTION AND STATUS AND AREAS OF APPLICATION

5.2.1 Doppler Radar Winds

5.2.1.1 *Microwave Systems*

Microwave radar should be viewed as a potential tool for providing wind measurements in precipitation, but longer wavelength radar is needed for wind measurements in the optically clear atmosphere. Synthetic Aperture Radar (SAR) methods have very high potential for providing quantitative global measurements of precipitation, data that are important in many meteorological problems. However, the measurement of either precipitation or winds in precipitating systems requires very large vertical apertures to generate (real) narrow beams to discriminate precipitation levels and to separate precipitation and ground echoes. Such a system would be very costly and require extensive processing and/or communication bandwidth. However, it might be justified on the basis of multi-parameter data, including scatterometry, but it is not justifiable for providing only winds. Therefore, the microwave radar techniques for spaceborne winds should be pursued in conjunction with global precipitation measurements and further developments of SAR. The potential for measuring winds from space is considered poor because of aperture size limitations and the power required.

5.2.1.2 *UHF/VHF Radar*

The applicability of the "profiler" technology (UHF/VHF[1] Doppler radar) to spaceborne platforms seems very unlikely in the near future because of the antenna size and transmitted power required. The ground-based profiler should be viewed as a local source of data input to a global wind system. It will also be an important source of ground truth for any spaceborne system because of its accuracy and resolution. The widespread deployment of profilers expected during the next 10 years means that there will be numerous opportunities for single-point ground truth verification. In addition, there will be profiler networks that will allow an assessment of spaceborne measurements that are averaged over large areas. The potential for

[1] Ultra High Frequency/Very High Frequency

measuring winds from space is considered very poor because of aperture size limitations and the power required (10s of kW).

5.2.1.3 *Bistatic Systems*

A VHF radar or microwave beacon in geosynchronous orbit could be used with ground-based receiver arrays (or the receiver array could be an orbiting satellite with a ground-based transmitter analogous to stellar scintillometer techniques). This geometry exploits the increased signal that bistatic systems obtain relative to monostatic radar. The technique requires theoretical study to assess feasibility and to determine if such a system could provide winds globally.

5.2.2 Scatterometer

The launch of the Seasat A satellite in June 1978 provided a new source of wind data over the world's oceans for meteorological and oceanographic research. On board the satellite, an active microwave sensor known as the Seasat A Satellite Scatterometer (SASS) measured the backscatter from the wind-produced surface capillary-gravity waves (about 1 to 3 cm in wavelength), which can be used with an empirical algorithm (model function) to infer surface wind stress and wind vectors (Jones *et al.,* 1982; Schroeder *et al.,* 1982; Woiceshyn *et al.,* 1986). The marine wind vectors are computed for a height of 19.5 m above the sea surface and corrected for the influences of heat and moisture fluxes to neutral stratification conditions. Seasat provided high resolution (about 50 km) surface wind measurements, but each observation specified up to four possible wind directions due to the nature of the instrument characteristics. One wind direction was correct, and the rest so-called "aliases" or "ambiguities." About 96 days of Seasat scatterometer data were collected during the summer of 1978. Data from SASS have been used in a number of meteorological and oceanographic studies, although the preliminary studies have found the impact on global large-scale atmospheric analyses and forecasts to be marginal (e.g., Baker *et al.,* 1984; Duffy *et al.,* 1984). However, further work is continuing regarding the assimilation, impact, and use of the Seasat SASS data.

With regard to meeting performance specifications, Woiceshyn *et al.* (1986) noted that SASS only met specifications in an rms sense for the region where final "tuning" and validation were conducted (between Iceland and Scotland). They determined that an improved wind retrieval systems is necessary for SASS wind data to meet the required performance specifications. To accomplish this, Woiceshyn *et al.* suggested that the wind retrieval algorithms need to be additionally corrected for the backscatter variation due to the effects of viscosity on the shortwave structure that is contributing to the backscatter measurements.

New scatterometer instruments have been approved for the NROSS, ERS-l and RADARSAT satellites. In the new instrument designs, the antenna number has been changed from two (the SASS design) to three on each of the spacecraft to alleviate the directional ambiguity problems that plagued the Seasat instrument. On NROSS, to correct for contamination in the field of view, or for flagging degraded backscatter measurements due to liquid water (about 5% of the time), the passive microwave measurements from the SSM/I instrument will be utilitzed. The NROSS mission-duration goal is 36 months with launch planned for 1990.

5.2.3 Passive Triple-Etalon Fabry-Perot Interferometer

The Upper Atmosphere Research Satellite (UARS) is expected to provide, for the first time, a global data set required to analyze the chemistry, dynamics, and radiation budget of the stratosphere and mesosphere. The goals of the program are to understand the mechanisms controlling upper atmosphere structure and processes and to understand the response of the upper atmosphere to natural and human perturbations.

The High Resolution Doppler Imager (HRDI), described in Skinner *et al.* (1985), is the primary instrument for measuring the dynamics of the stratosphere and mesosphere. The HRDI instrument is a triple etalon Fabry-Perot interferometer that views the Earth's atmosphere through a two-axis telescope from a spacecraft altitude of 600 km. Measurements of the Doppler shifts in the atmospheric absorption and emission features are made by performing a wavelength analysis on the detected light by spatially scanning the interference fringe plane with a multichannel array detector. Line-of-sight winds will be taken in two directions allowing the wind vector to be formed.

5.2.4 Electro-Optical Phase Modulation Correlation Wind Sensor

Doppler shifts in the thermal emission spectrum of the atmosphere in the 20 to 120 km altitude range can be sensed passively with the Electro-Optical Phase Modulation correlation wind sensor now under development at NASA Jet Propulsion Laboratory (JPL). The observations are made in a limb viewing mode. Simultaneous measurements of the concentrations of stable atmospheric species and temperature profiles may also be made.

Laboratory measurements and simulations have been performed. The electro-optical phase modulator and cooler are still to be developed. The potential for space deployment is considered good. An accurate knowledge of the spacecraft attitude is required (0.1 mr to 0.2 mr), with < 3 mr required for the pointing attitude.

5.2.5 Enhanced Geosynchronous Satellite Wind Measurements

Methods for tracking cloud motion have been investigated since the early 1970s. To further enhance the wind measurement capability with this approach (discussed in Section 4.2), a larger spacecraft and sensor with a > 1 m telescope is under investigation. A straightforward extension of the present technology (3-axis-stabilized spacecraft) would be required. The required horizontal resolutions are 200 m in the visible and 500–1000 m in the thermal infrared. For tracking low level clouds over land, the image interval should be 1 min and the image should cover areas $\geqslant 1000 \times 1000$ km. For low level cloud-tracking over water the temporal resolution should be 3 min for areas $\geqslant 3000 \times 3000$ km. Middle and high cloud-tracking will require an image interval of 6 min, also for an area $\geqslant 3000 \times 3000$ km. Precise attitude control and determination ($\geqslant 200$ m ground accuracy) would also be required as well as real-time interactive control of the spacecraft. Several studies on the required radiometer have been performed. The winds obtained would primarily be for mesoscale studies (e.g., severe local storms, tropical cyclones).

5.2.6 Lidar Systems

5.2.6.1 *Aerosol Structure Correlation Technique*

This technique is applicable in the lower troposphere where aerosol targets are plentiful. An advantage of this system is that it requires simple incoherent backscatter measurements. A ground-based system works successfully for convective regions and has demonstrated wind-speed accuracies < 1 m s^{-1}. However, the system has not been proven for stable layers or outside the convective boundary layer. Also, a space-qualified laser requiring ~ 100 watts of power, on the average, is needed. The potential for space deployment needs to be assessed. Very good spacecraft attitude information would be required (<~ 0.1 mr).

5.2.6.2 *Incoherent Excimer Doppler Lidar Systems*

Until recently, narrow bandwidth, moderate energy lasers in the ultraviolet have not been available and, therefore, have not previously been considered for active wind sensors. Following the recent development at NASA JPL of a single longitudinal mode xenon chloride (XeCl) laser, an ultraviolet Doppler lidar system is now an attractive possibility. The technique is presently in the stage of active development. If demonstration of a ground-based system proves successful, a compact, mobile system could be useful in providing wind data for a variety of applications (e.g., monitoring microbursts mentioned in Section 2.2). In general, the coherence properties of short-pulse lasers render coherent detection methods inappropriate and the optimum choice for an incoherent detector is a multiple etalon Fabry-Perot interferometer using an imaging detector to observe the fringe pattern. Such devices have been developed at the University College in London, England and successfully applied to the measurement of atmospheric winds by passive techniques (see Section 4.1). A single etalon system with a similar imaging detector was used on the NASA Dynamics Explorer satellite, and another will be flown on UARS (see Section 5.2.3). When coupled, the single-mode XeCl laser and the capacitance-stabilized interferometer provide a system with the potential for making accurate wind measurements.

The spaceborne instrument could be applicable from the surface to 30 km. A ground-based demonstration is planned as the necessary components are now available. The stability of the intrapulse frequency has been demonstrated at 100 mJ/pulse. The detector hardware has been space qualified and the laser hardware should be space qualifiable. However, additional system performance studies are needed.

5.2.6.3 *Incoherent 0.5 μm Nd:YAG Doppler Lidar*

The instrument is applicable for measuring tropospheric winds. The 0.53 μm incoherent Doppler lidar system uses a multiple etalon Fabry-Perot interferometer as the spectral dispersive element to separate different wavelengths into different conical angles, analogous to the detector for the excimer Doppler lidar system. A multi-ring image plane detector measures the wavelength spectra of both the laser pulse and backscatter signal, the difference being proportional to the Doppler shift velocity.

The 0.53 μm Doppler lidar being developed at Radio Corporation of America (RCA) consists of a single frequency, Nd:YAG (Neodymium dopant in a host crystal of Yttrium Aluminum Garnet) laser, a receiver telescope with associated optics, a Fabry-Perot interferometer utilizing an image plane detector and a multichannel, high speed data system to acquire, store and process the data. Preliminary results from atmospheric experiments have demonstrated the capability of this system to differentiate between the narrow, Doppler shifted backscatter spectrum associated with aerosols and clouds from the spectrally broader molecular return. The hardware should be space qualifiable, but additional studies are needed. Eye safety is not an issue with this system since the illumination is spread over a larger area with incoherent detection than with coherent detection.

5.2.6.4 *Coherent 1.06 μm Nd:YAG Doppler Lidar*

The instrument is applicable for measuring winds in the troposphere and lower stratosphere and the technique is the same as that for the CO_2 lidar (see Section 5.2.6.5). Conceptual studies have been performed and a ground-based system is under construction. Diode pumping techniques, which still need to be developed, are necessary to achieve efficiency. These techniques are more desirable than the conventional flash lamp approach because they potentially have longer lifetime, greater efficiency and would be more suitable for space flight. Neither the pulse energy required nor the heterodyne detection that is required has been demonstrated. Eye safety requirements cannot be met with a 1.06 μm laser. On the other hand, the compactness of the system and expected "long" lifetime are extremely attractive. Consequently, work should be directed toward developing diode-pumped solid state laser transmitters with wavelengths > 1.4 μm for eye safety reasons.

5.2.6.5 *Coherent CO_2 Doppler Lidar*

The instrument is applicable for measuring tropospheric winds with a demonstrated accuracy of 0.5 m s^{-1} (Hall *et al.*, 1984) and stratospheric winds up to possibly 20 km, depending on the availability of suitable aerosols. Coherent CO_2 lidar systems have demonstrated accurate wind measurement capability since 1968. An airborne scanning lidar, developed by NASA Marshall Space Flight Center (MSFC) in 1970, continues to be used for research purposes. A design study for a Shuttle experiment (Lockheed, 1981) was conducted to demonstrate the feasibility of a spaceborne CO_2 lidar system. More recently, Gurk *et al.* (1985) have shown that the CO_2 lidar could be accommodated on the RCA advanced TIROS-N satellite. The proposed design uses a 9.11 μm, CO_2 Transverse Excited Atmospheric (TEA) laser producing 10 J/pulse, operating through conically scanning optics of 1.25 m diameter. At the suggested 2 pulse per second firing rate, measurements of the two-dimensional wind field could be made at approximately 50 km resolution averaged from more closely spaced footprints, with finer resolution possible in a step scan, probing mode.

The experimental equipment design exploited the size and power capabilities of TIROS-N, and allowing for an orbital attitude of 800 km vs the Shuttle's 300 km, the study showed that an operational payload could weigh around 240 kg, and have power requirements well within the spacecraft capability.

A study has been completed for a Spacelab pallet experiment (Fitzjarrald *et al.*, 1985) to use an existing 2 J laser design on the Shuttle. The proposed Shuttle experiment (Shuttle Coherent Atmospheric Lidar Experiment or SCALE) would provide enough sensitivity to make global backscatter and wind measurements from a 200 km altitude. The remaining technological issues that need to be addressed before launching a free-flying Doppler lidar should be addressed by such an experiment, including laser space qualification, lag angle compensation, signal processing and remote optical alignment. Some crucial scientific questions regarding the global backscatter magnitude and distribution would also be addressed along with the problem of beam scanning to obtain a meaningful average wind value. No new technology was found to be needed in either the laser space qualification or the Spacelab pallet accommodations. Weight, thermal, and data management requirements were found to be well within the standard Spacelab pallet capabilities. Power availability on the Spacelab pallet is sufficient for operation at 25 Hz, which allows sufficient averaging to overcome laser speckle (caused by the coherent illumination) problems. The telescope was designed to be fixed in the Shuttle bay, and the entire orbiter rotated to give beam scanning to obtain wind measurements for certain regions.

Ground-based and airborne measurements of tropospheric winds have been conducted with the CO_2 lidar for the past 15 years. Cross comparisons have been made with other lidars, towers, aircraft, and radar. An extensive comparison has been made between theoretical and experimental analyses showing good agreement. The space qualifications study for a 2 J/pulse laser has been completed, and no significant problems are anticipated for a Shuttle-based lidar. Lag angle compensation still needs to be demonstrated. Laser lifetime studies are needed (catalytic studies, electrode life, window degradation). The potential for space deployment is considered good with high laser efficiency.

5.3 RESOLUTION, ACCURACY, AND COVERAGE

The expected horizontal, vertical, and temporal resolution, measurement accuracy and coverage for the various wind sensors are contained in Table 5.1. For this comparison, a single polar orbiting satellite has been assumed for the lidar systems.

TABLE 5.1 Expected resolution, measurement accuracy, and coverage of the various wind sensors.

	Resolution				
Instrument	Horizontal (km)	Vertical (km)	Temporal (h)	Accuracy ($m\ s^{-1}$)	Coverage
Microwave radar	Aperture dependent	0.15	< 0.1	1	In precipitating systems
UHF/VHF radar	10	0.3	< 0.1	1	Regional
Scatterometer	25	—	12	+ 10% windspeed + 20° direction	Global-oceanic surface
Fabry-Perot interferometer	125	4	~ 24	< 5	+ 74° latitude-stratosphere and mesosphere
Gas correlation technique[1]	150[2]	5	~ 24	< 5	Near-global[3]-stratosphere and mesosphere
Enhanced geosynchronous measurements	~20 km-low clouds ~50 to 100 km-high clouds	—	0.1 to 1	≤2-low clouds ≤3-high clouds	~1000 km^2 (regional) 10,000 km^2 (large-scale)
Lidar					
Aerosol correlation technique	1 to 10	0.05	12	1 to 3	Global-lower troposphere
Incoherent excimer Doppler	50[4]	0.2 to 1	12	To be determined	Global[5]-troposphere
Incoherent 0.5 μm Doppler	50[4]	0.2 to 1	12	To be determined	Global[5]-troposphere
Coherent 1.06 μm Doppler	50[4]	0.2 to 1	12	To be determined	Global[5]-troposphere
Coherent CO_2 Doppler	50[6]	0.2 to 1	12	1 to 3	Global[5]-troposphere

[1] Electro-optical phase modulation correlation wind sensor.
[2] Along spacecraft track; 200 km line-of-sight resolution.
[3] Dependent on platform orbital inclination.
[4] Represents an average, the footprint is much smaller. The 50 km suggested resolution remains to be demonstrated.
[5] Limited by middle and lower clouds; assumes an orbit of 800 km.
[6] Represents an average, the 50 km suggested resolution remains to be demonstrated.

5.4 RECOMMENDATIONS

From the material presented it is recommended that:

1. Ground-based and airborne measurements by CO_2 Doppler systems be continued.
2. Ground-based wind measurements be demonstrated with incoherent Doppler lidars, and at other wavelengths for coherent Doppler lidars.
3. Advanced lidars be developed in order to obtain global aerosol backscatter measurements (0.35 μm to 11 μm).
4. Contingent on successful ground-based demonstrations, detailed feasibility studies, similar to the CO_2 studies, be conducted for incoherent Doppler lidars and the coherent Doppler lidars at other wavelengths.
5. Development of passive sensors to measure stratospheric winds be continued.
6. The suggested improvements for obtaining better cloud-track winds should be implemented.
7. The existing Seasat data should be exploited further to improve scatterometer accuracy by: (1) developing an improved model function (backscatter-to-wind transfer algorithm), (2) incorporating environmental parameters (e.g., sea surface temperature, moisture and heat fluxes, etc.) into a physically based model function, and (3) developing improved alias removal techniques.
8. Further work be done to sharpen the user requirements for wind measurements.

Specifically related to Doppler lidar sensor development, the following recommendations are made:

9. Global aerosols should be measured to confirm adequate aerosol backscatter levels to support Doppler lidar measurements from space.
10. The lag-angle compensation for both coarse and fine control of the beam-pointing should be demonstrated (can best be done in a spaceborne test).
11. A spaceborne Doppler lidar wind measurement system should be demonstrated.
12. The onboard Doppler lidar data processing and transmission should be demonstrated to verify algorithm suitability (from either aircraft or space).
13. A Doppler lidar system with a compact, efficient, 6 to 10 J laser should be built and flown on an aircraft.
14. To accomplish these demonstrations, and upon further verification of the required global aerosol distribution, a vigorous program for the construction and test of the necessary ground-based, aircraft-borne, and spaceborne lidars is recommended, starting in FY86 and completed by the early 1990s, leading to the construction of a wind-sensing system as part of the Earth Observing System (Eos).

SECTION 6

ATMOSPHERIC AEROSOLS AND RELATED TRACERS

6.1 BACKGROUND

Any technique for measuring winds from space platforms requires some remotely detectable tracer that is advected or affected by the wind. Such tracers, whether they are clouds, aerosols, gases and vapors, turbulent eddies, or ocean waves, may not be uniformly available or accessible. We need to define what is known about the various tracers in the context of wind measurements, and to identify gaps in our understanding. This will allow the development of wind sampling strategies designed to minimize errors. The purpose of this section is to make recommendations for further atmospheric research on aerosols and aerosol optical properties that needs to be performed as part of the development of a global wind observing system.

The main focus of this section will be on Doppler lidar wind measuring systems. Although important, less attention will be given to other active techniques, such as radar profilers, and to passive techniques such as spectroradiometry, and pattern correlation of clouds, water vapor, or aerosols.

6.2 ATMOSPHERIC CONSTITUENTS REQUIRED FOR LIDAR MEASUREMENTS

The intensity of the laser energy available to the detector of a lidar system is proportional to the amount of backscatter from atmospheric aerosols. The intensity also suffers extinction as the radiation passes through clouds and is absorbed by atmospheric gases. At the present time there are significant knowledge gaps concerning the global distribution of aerosols and clouds. These gaps must be narrowed before realistic modeling of lidar performance can be accomplished. We need global aerosol backscatter coefficients for the specific wavelengths of anticipated laser sources from the near ultraviolet to the 10 μm infrared, from the surface to 20 km in height, for each of the seasons. We also need global cloud-free line-of-sight statistics to various depths in the atmosphere, from the tropopause to the surface. These data should be accurate to within 20%, the height resolved to 1 km increments, and obtained for each of the seasons. The number of independent regional/seasonal data sets of aerosol backscatter and cloud-free line-of-sight statistics need to be determined, but is probably on the order of 10 to 20.

Since cloud-track winds would naturally complement lidar winds, correlative data sets on cloud evolution and advection characteristics are also needed. Lidar data can be used to determine the height of cloud features that might obstruct further penetration of the laser beam.

6.2.1 Current Knowledge of Tropospheric Aerosols

Tropospheric aerosol populations are considerably more diverse in concentration, size, shape, and composition than stratospheric aerosols. This diversity reflects the natural variation in the sources, transport mechanisms, *in situ* modification processes, and removal mechanisms in the troposphere.

Major constituents of the fine particle fraction ($\sim < 1\ \mu m$ diameter) include sulfates (sulfuric acid, ammonium bisulfate, and ammonium sulfate) from gas-to-particle conversion, followed by *in situ* chemical reactions and coagulation, and organics and soot from biomass combustion. Major constituents of the coarse particle fraction ($\sim > 1\ \mu m$ diameter) include salts from the ocean surface, crustal material from exposed soil surfaces, and pollen grains from vegetation. In addition, water can condense on aerosol particles between about 0.01 and 10 μm diameter.

At lower altitudes, such as in the marine and continental boundary layers, aerosol concentrations are generally high enough to provide more than enough backscatter at any wavelength from the visible to the near infrared. However, at the higher altitudes, aerosol concentrations may be too low to allow accurate Doppler lidar wind measurements. The lowest aerosol concentrations are typically found at high tropospheric altitudes or in remote oceanic or polar regions, where aerosol transport is weaker, and in low wind conditions over the oceans or in the winter season, when aerosol source strengths are reduced.

In these situations, the tropospheric aerosols appear to consist of a fine mode composed primarily of sulfates with a typical diameter (volume-weighted) of a few tenths of a micrometer, and of a coarse mode composed primarily of crustal material, with a typical diameter (volume-weighted) of about 1 to 2 μm. Sulfate and crustal concentrations can vary independently from about 0.01 to 1 $\mu g\ m^{-3}$.

For this type of aerosol population, aerosol backscatter generally decreases rapidly with wavelength (λ). However, the ratio of the mean aerosol backscatter to Rayleigh (molecular) backscatter increases from roughly 10 percent or less at near ultraviolet wavelengths to several orders of magnitude at CO_2 wavelengths, because Rayleigh scattering decreases as λ^{-4}. Higher concentrations of coarse particles reduce the wavelength dependence of aerosol backscatter in the visible and near infrared wavelengths and dramatically enhance backscatter values at CO_2 wavelengths. Additional backscatter enhancements are possible for wavelengths near strong aerosol absorption resonances. Further enhancements are possible in the wings of the resonance peak for nonspherical particles, such as ammonium sulfate and dust.

If aerosol concentrations are extremely low in large, connected spatial/temporal domains, then accurate wind measurements in those regions will be difficult to obtain with a Doppler lidar. The spectral variability of aerosol backscatter in these "clean" conditions will play an important role in tradeoff studies to optimize the Doppler lidar system design.

Our lack of knowledge of the physical properties of aerosols in the upper troposphere is compounded by the uncertainties in the processes of vertical transfer of aerosols from the stratosphere to the troposphere. This may occur as sedimentation or via tropopause folding events. As a result of these processes, the region of the upper troposphere between roughly 5 km and the tropopause may contain a considerable quantity of volcanic material during the months or years following stratospheric volcanic injection (Post, 1985). The detailed structure of these aerosols (i.e., size distribution, composition, and spatial/temporal variability) is largely unexamined.

6.2.2 Current Knowledge of Stratospheric Aerosols

Stratospheric aerosols are believed to be formed from sulfur-containing gases that diffuse upwards from the troposphere or are directly injected into the stratosphere by volcanic eruptions. In both cases, physical and chemical processes result in the formation of liquid sulfuric acid aerosols. Under nonvolcanic conditions, the number-weighted modal radius for these aerosols is generally less than 0.1 μm; during the period following volcanic input a significant number of larger particles are formed. Satellite observations have shown background nonvolcanic stratospheric aerosols to be evenly distributed globally, with peak mixing ratios occurring at altitudes of about 10 km above the tropopause. Above 30 km at the equator, and at lower altitudes at other latitudes, the aerosol concentrations are only a small fraction of those at the peak layer. Volcanic aerosols are distributed very nonuniformly immediately after a volcanic eruption, and, over a period of months, spread in both latitude and longitude. Recently injected volcanic material also contains solid particles which are removed fairly quickly by sedimentation. Sedimentation similarly occurs in the large sulfuric acid aerosols formed after an eruption, the newly formed layer gradually decreasing in altitude and losing material into the troposphere.

Modeling of the scattering properties of stratospheric aerosols at times other than immediately after an eruption is in principle simpler and easier to carry out than for free tropospheric aerosols. Except just after volcanic injection, the majority of the aerosols are made of sulfuric acid and are spherical in shape. *In situ* measurements have been made on the acid concentration and on the particle size distribution, both quantities being required for calculation of optical properties. There is unfortunately a lack of information on the concentration of particles with sizes between 0.25 and 1.0 μm, an important size range for post-volcanic aerosols. Lidar data at both visible and infrared wavelengths is available to assist with modeling studies. Modeled scattering cross sections at 10.6 μm for background stratospheric aerosols show peak values of 10^{-11} to 10^{-10} m^{-1} sr^{-1}. Following a major eruption, such as that of El Chichon, these values may increase to 10^{-9} or even 10^{-8} m^{-1} sr^{-1}.

6.3 SAMPLING STRATEGIES AND ERROR ANALYSES

Both incoherent and coherent Doppler lidar techniques represent new and nonconventional perspectives on atmospheric motions. Although the sample volumes and the means of detecting the Doppler shift are different, both techniques provide a measure of the atmospheric motion only along a radial direction. Without a direct measurement of the crossbeam component, radial measurements at several look angles must be combined to achieve estimates of the total horizontal wind vector. The lack of spatial and temporal coincidence of the independent radial data requires the development of algorithms to combine these data into a single estimate of the u and v wind components.

6.3.1 Passive Doppler Interferometer/Spectrometer

The only wind measurement technique which appears to be suitable above the middle stratosphere is the passive interferometer/spectrometer as discussed in Section 5.2.3. For this sensor, the wind tracers are naturally occurring molecular species such as O_2 and H_2O. The measured winds are derived from limb-sounding, with a line-of-sight path length at each altitude of about 150–200 km, and an along-track path length of about 250 km. Thus, the wind measurement accuracy of the technique depends, among other factors, on the spatial uniformity of the molecular tracers at each altitude. Studies should be undertaken to verify that the molecular tracers are, in fact, well mixed so that standard atmospheric profiles can be used in the inversion process. The sensitivity of the inversion process to deviations from a well-mixed atmosphere should be determined. The sampling strategy appears to be optimized for the method in which the sensor obtains its measurements.

A passive triple-etalon Fabry-Perot interferometer which is scheduled to fly on UARS and has flown on Dynamics Explorer (Spencer *et al.,* 1981) should significantly enhance our knowledge of the stratospheric wind field. This instrument would complement a tropospheric global wind observing system.

6.3.2 Active Doppler Impediments

Atmospheric impediments include molecular absorption, extinction due to Rayleigh scattering and aerosol scattering, and loss of spatial coherence due to turbulent refractive index eddies. These processes all cause various amounts of signal loss as the lidar radiation propagates to and from the scattering volume of interest. Scintillation (intensity fluctuations due to turbulence) is not important within the microsecond time scales of the measurement and would only affect the pulse-to-pulse return signal fluctuation in a minor way. Cloud cover also affects the measurement by obscuring the portion of the atmosphere below the clouds, unless the clouds are thin cirrus, which cause only a loss of a few dB.

Our knowledge of the losses due to Rayleigh scattering are well known and can easily be included in system performance calculations for particular pointing geometries. The Rayleigh and aerosol extinction are nonnegligible for the midvisible and shorter wavelengths, with the aerosol extinction becoming a factor only when propagation extends to the lower 2–3 km of the atmosphere. Since the aerosol backscatter is generally high in this region, the corresponding loss due to aerosol extinction can be tolerated.

The molecular absorption loss is a consideration in the infrared and in the ultraviolet at wavelengths shorter than 330 nm. The shorter ultraviolet wavelengths suffer strong absorption due to stratospheric ozone. The infrared wavelengths of the CO_2 laser will be affected by atmospheric CO_2 and H_2O absorption. The proper choice of a CO_2 transmitter wavelength, namely that of a rare isotope CO_2 molecule which does not overlap a water vapor line, will result in loss due to water vapor continuum absorption only in the lower 2 to 4 km of the atmosphere. Because the round-trip vertical attenuation due to a strong atmospheric CO_2 line in the 9–10 μm region is approximately a factor of two, and pointing at an off nadir angle θ implies multiplying by the vertical optical depth sec θ, a substantial benefit is obtained by operating at a rare isotope line. The spectroscopy of molecular atmospheric absorbants is known well enough to calculate these losses accurately for various atmospheric temperatures and humidity conditions. Examples of the molecular scattering and absorption losses, as they affect the various coherent and incoherent lidars, are treated in NOAA feasibility studies (Huffaker, 1978; Huffaker *et al.,* 1980) and by Menzies and Kavaya (1985).

The state of knowledge of cloud cover over various regions of the globe, as it pertains to the impact on Doppler lidar measurements, is inadequate for detailed performance estimates. Further studies are needed not only on global coarse resolution percentages of cloud cover but also on statistics (Snow *et al.,* 1985). The work of Snow *et al.,* which concentrates on fine scale studies over specific, small regions, may prove to be applicable to general global cloud cover statistics. The small-scale statistics can be applied to the study of the penetration capability of the small lidar beam ($\sim$ 10–20 m diameter in the troposphere) as it propagates to and from the backscattering volume of interest.

6.4 CURRENTLY PLANNED EFFORTS

The SAGE II satellite is currently in orbit making multiwavelength observations on stratospheric aerosols, NO_2, O_3 and water vapor. The stratospheric aerosol data base will be employed to expand the present aerosol climatology, the multiple wavelengths being used to deduce information concerning the aerosol size distribution and the water vapor concentrations to assist with microphysical modeling. In addition, as for SAGE I and SAM II, extinction measurements will also be made in the upper troposphere. SAM II satellite measurements will continue to be available.

There are in existence several lidar programs to obtain quantitative measurements of stratospheric aerosols. These include an extensive chain of stations making measurements in the visible region of the spectrum as well as a more limited number of stations making measurements at CO_2 wavelengths (NOAA, NASA JPL, NASA LaRC). NASA Langley Research Center (LaRC) is currently planning an airborne lidar flight in January 1986 to make ruby/Nd:YAG measurements of arctic stratospheric aerosols.

In situ measurements of the extinction coefficient with an integrating scattering nephelometer have been obtained for over ten years at several remote sites for several wavelengths (0.45, 0.55, 0.70, and 0.85 μm). These measurements are part of NOAA's Geophysical Monitoring for Climatic Change (GMCC) program. A particularly important site in the GMCC network is located at the Mauna Loa Observatory in the Hawaiian Islands. The Mauna Loa site can be used to monitor the influence of both residual dust plumes and ultra-clean air on aerosol optical properties in the upper troposphere over the central Pacific ocean. These measurements are expected to continue.

The data base on aerosol backscatter at CO_2 wavelengths is growing rapidly. Three of the largest data sets have been obtained with ground-based pulsed CO_2 Doppler lidars by NOAA ERL WPL and NASA JPL, and with an airborne, continuous-wave CO_2 focused Doppler lidar by the Royal Signals and Radar Establishment (RSRE) in the United Kingdom. None of these data sets has been analyzed in great detail, particularly the RSRE data set. Within the next several months, these data sets will be processed and analyzed using standard statistical methods as well as individual case studies.

NASA Marshall Space Flight Center is developing a preliminary global-scale aerosol backscatter model. This model, which will incorporate measurements from several aerosol data bases, will describe the optical and microphysical properties of the background aerosol. Particular attention will be paid to defining the spectral variability for backscatter cross sections of the background aerosol. A limited description of the spatial and temporal variability of the background aerosol will be included.

Space-based Doppler lidar strategies are currently being developed at NASA MSFC. That effort is focused on three objectives: (1) optimum scan/pulse parameters, (2) optimum wind computation algorithms, and (3) required sample density to achieve desired accuracy and representativeness. Error analyses are, at present, limited to those associated with sampling pattern, scan geometry and wind variability. There are planned efforts to update the earlier studies on system and radial wind measurement errors.

Within research centers (e.g., NOAA, NASA, University of Wisconsin, Colorado State University) there are continuing efforts to perfect cloud-tracking techniques and to solve some of the problems associated with the height assignment of wind estimates and the interpretation of the apparent wind motion.

The use of radar wind profilers continues to expand in a variety of applications and diverse geographical regions. Our present knowledge of radar refractive index structure C_n^2 will undoubtedly be expanded in the future to oceanic and tropical areas. When the present understanding of C_n^2 is improved, and the availability of large, high power space stations is assured, it may be desirable to examine the feasibility of such profilers in orbit for global wind measurements.

6.5 AREAS REQUIRING FURTHER STUDY

Information is still required for many aspects of the global distribution of aerosol optical properties. These include particle size distribution, concentration, composition and shape. In addition, the statistical distribution of aerosols in time and space and how this relates to aerosol sources are largely unexplained. The influences of volcanic injection, tropopause folding, global transport, and cloud pumping need further study. Multiwavelength characterization of aerosol optical properties from the ultraviolet to 11 μm, both by direct measurement and theoretical calculation from measurements of aerosol microphysical properties, is required. Special phenomena such as the formation of polar stratospheric clouds and thin cirrus veils in the tropics represent other areas of insufficient knowledge.

Considerable uncertainty exists at this time on the extrapolation of aerosol measurements from very large, horizontally averaged sample volumes (e.g., from SAM/SAGE) or from the very small volumes measured by *in situ* particle samplers to the expected optical properties in the lidar sample volume. These uncertainties probably arise from poor counting statistics in the small sample volumes and from averaging of spatial inhomogenities in the large sample volumes.

Previous measurements have shown that aerosols are frequently found in well-defined layers in both the troposphere and the stratosphere. However, little is known about the nature and extent of this stratification in remote regions, particularly in the troposphere over the oceans. Information is needed on the depth and horizontal dimension of these aerosol layers, the aerosol variability within the layers, the relationship of the layer to the local meteorological setting, and the life cycles of the layers. Such layers are important because they may provide the only backscatter targets in an otherwise "clean" region.

The possibility exists of finding very low concentrations ($\ll$ 1000 m^{-3}) of very large particles ($\gg$ 1 μm) in the atmosphere, yet the concentration could still be sufficient to dominate the backscatter in the large lidar sampling volumes. Few optical particle counters have volume sampling rates large enough to detect such particles, but their presence could be very important. Aerosol inhomogenities on small scales (< 50 km) can have a significant impact on the wind estimates derived from an array of lidar shots. Likewise, inhomogenities on smaller scales ($\sim$< 1 km) can affect the representativeness of radial wind estimates from single lidar shots. The probability of encountering inhomogenities at various scales is not well established.

The present understanding of cloud cover statistics (e.g., probability distribution of cloud sizes for various cloud types and geographical regions) is probably not adequate for detailed, quantitative estimates of the data loss at various altitude levels due to obscuration of the atmospheric regions below the clouds. Further studies using aircraft visible imaging would be helpful. Airborne lidar experiments would also be a valuable source of this type of information. The airborne lidar data can also directly provide percentage penetration estimates over regions with various types of partial cloud cover. It would greatly help to have scanning capability in order to assess the influence of nadir angle on probability of penetration.

Estimates of obscuration using nadir views from a visible imager may be misleading in this regard.

6.6 RECOMMENDATIONS

The understanding of aerosols and aerosol optical properties, particularly as they relate to proposed wind determination techniques, has greatly expanded during the past few years. This expansion has lead to an awareness of the need for further research to:

1. Use lidar, *in situ* measurements, and remote optical techniques to improve the characterization of the free tropospheric and lower stratospheric aerosols on a global scale.
2. Understand the effects of aerosol/wind speed correlation on the radial wind measurements, determine optimum shot density and distributions to achieve accuracy objectives, and develop criteria for identifying the areas and situations when reliable Doppler lidar winds can be expected because of the unique form of the wind information yielded by Doppler lidars (both coherent and incoherent). This basis should include the global aerosol distribution and cloud-free line-of-sight statistics.
3. Use the existing and ongoing tropospheric data sets from SAGE II and the Mauna Loa Observatory to improve the global climatology of the free tropospheric aerosol.
4. Use satellite imaging to investigate the distribution of aerosol plumes over the oceans.
5. Establish a network of ground-based cross-calibrated pulsed lidars to make coordinated measurements of aerosol backscatter and to establish local backscatter climatologies at CO_2 laser wavelengths. This should include one or more stations in the southern hemisphere.
6. Establish improved calibration techniques for visible and near IR lidar systems to allow quantitative aerosol backscatter measurements to be made in "clean" tropospheric air masses.
7. Initiate a coordinated global-scale aerosol backscatter measurement program. These programs should include airborne over-flights of all ground or ship stations as well as special missions to provide backscatter measurements over a wide range of spatial scales.
8. Use any future shuttle-based lidar mission to measure backscatter cross-sections on a global scale.
9. Expand the high altitude aerosol laboratory at Mauna Loa to include simultaneous CO_2 lidar backscatter measurements and *in situ* measurements of aerosol microphysical and chemical properties.
10. Develop a global scale aerosol model which describes the spatial and temporal distribution of aerosol backscatter and the spectral variability from the ultraviolet to the middle infrared.
11. Investigate special geophysical events, such as volcanic eruptions, as they illustrate the extent to which aerosols are transported and modified.
12. Attempt to improve the understanding of the probability distribution of cloud sizes for various cloud types and geographical regions using aircraft visible imaging and lidar measurements. Percentage penetration estimates should also be obtained over regions with various types of partial cloud cover using airborne lidar.

SECTION 7

AIR FORCE DEVELOPMENTS TOWARD SPACE WIND SENSING

7.1 INTRODUCTION

The Defense Meteorological Satellite Program (DMSP) Office has designed a program for developing an operational lidar wind sensor. The United States Air Force is advocating the measurement of winds by the use of Doppler lidar in support of the increasing military requirements. The second justification for Doppler lidar is for forecast improvement, especially tropical storm movement. The following military activities would benefit from increased knowledge of global wind profiles:

1. More effective planning by command and control agencies for force reconstitution following a hostile attack.
2. Special forces and rescue/recovery operations have a high priority need for fine-scale, accurate wind data for paradrops, deception/concealment activities, thermal stress/-wind chill planning, and target scene forecasts.
3. Detailed spatial and temporal resolution of wind fields can assist decision-makers during major aircraft movements and contingencies by minimizing flight times, minimizing fuel offloads, and maximizing airlift capability.
4. Other operations which will benefit from improved wind and temperature information include data for programming missile reentry calculations, improved support to high performance strategic reconnaissance aircraft, and better cloud forecasting in support of reconnaissance missions.

On the local scale, the following military activities would benefit from from increased knowledge of winds:

1. Army and Air Force aviation requires accurate wind fields, particularly for terrain following or terrain avoidance missions. In addition, existing and future electro-optical weapons systems require detailed aerosol and wind information for weapon selection, target acquisition and lock-on estimates.
2. Space launch activities, both Space Shuttle and Expendable Launch Vehicles, need improved wind information for stability and control during the initial launch phases.

Existing civil weather observing networks only provide wind, temperature, and water vapor data of sufficient quality and density over the continental United States and Europe during peacetime. The necessity for supporting the full spectrum of military contingencies drives the requirement for worldwide weather information at all levels of conflict. This dictates the development of a wind measurement system from a space platform. It is recognized that peacetime sources of weather data may not be available during times of conflict. These deficiencies dictate the development of a wind measurement system from a space platform. Initially, satellite-based techniques will only be able to support large-scale requirements. It appears that mesoscale requirements will be best satisfied by ground-based systems.

At present, the military has no direct measurement capability of wind profiles from a space platform. Doppler lidar has been demonstrated on the ground and from aircraft to be capable of accurately measuring wind speed and direction with good vertical resolution. The same potential exists for space applications. However, extensive development needs to be carried out before a space qualified Doppler lidar system is put into operational use.

7.2 CURRENTLY PLANNED EFFORTS

The atmospheric lidar programs within the DMSP and the Air Force Geophysics Laboratory (AFGL) include systems for stratospheric and mesospheric density and trace constituent measurements, a mobile CO_2 Doppler lidar, two non-Doppler mobile systems, and a balloon-borne lidar for backscatter measurements.

The spaceborne Doppler lidar program, managed by the Defense Meteorological Satellite Program Office, is divided into three phases. This long-term program is aimed at developing a lightweight lidar system, with as low power as possible, that will eventually meet the Department of Defense requirements. The first phase is the lidar sounder, a nonscanning, nadir viewing instrument, which may be flown as a space test program experiment. Since this experimental lidar is a nadir viewing system, no horizontal wind information can be derived from the data. There are several objectives associated with this first phase. The primary objective is to obtain global measurements and seasonal variations of aerosol concentration, cloud top heights, surface reflectivity and visibility. The second objective is to demonstrate spaceborne lidar technology, especially lidar reliability and life time in a space environment, and to observe the time degradation of the system. The third objective is to further define the size and power requirements of future operational lidar sensors. A polar orbiting free flyer such as DMSP or TIROS can provide the relatively long-term global coverage to meet these objectives.

The proposed second phase of the lidar wind sensor development effort is a nonscanning Doppler lidar system consisting of two lidar sounder type systems similar to that used in Phase I. One transmitter/receiver would look ahead of the ground track by 45° and the other look aft by 45°. The objective of this phase is to obtain some horizontal wind information as soon as possible for operational use.

The objective of the third phase is to develop a scanning Doppler lidar system capable of measuring the three-dimensional wind field. This sensor with its higher pulse rate, and, resulting larger power requirements, is anticipated to fly in the post-2000 time frame. The large power, weight and scanning optics required are anticipated to be key drivers of the spacecraft design.

7.3 RECOMMENDATIONS

Achieving a spaceborne lidar wind sensor will require advances in (1) simulations of lidar components, which will provide key information on items such as laser efficiencies, laser lifetimes, and data processing; (2) simulations of environmental factors including aerosol distributions, propagation effects, and cloud distributions; (3) simulations on the meteorological impact of lidar winds on weather analyses and forecasts; and (4) enhancements of laser and receiver technologies which will lead to space-qualified components capable of operating over a period of more than one year without degradation. Through an iterative feedback process between simulations and technological advances in lidar systems, the Air Force plans to develop a scanning Doppler lidar system capable of providing global wind fields. The recommendations to attain this goal include:

1. Conducting simulation studies with numerical weather prediction models to test the accuracy of weather analyses and forecasts when only satellite observations are used; the simulations should include cases in which the conventional data are denied over relatively small regions as well as cases in which large areas of the globe have access only to satellite data;

2. Fabricating a ground "brass-board" lidar wind measurement system in order to reduce the uncertainty in the assumptions which are made when scaling the lidar to a space platform;
3. Intensifying the development of space-based lidar data processing techniques and establishing trade-offs between onboard and ground-based processing;
4. Defining the critical subsystems and/or components for a space-based lidar wind measurement system, initiating a critical component development program, and identifying tests which can be implemented to evaluate the critical components; and
5. Expanding inter-disciplinary and inter-agency cooperation in an effort to accelerate the technological advances which are required for obtaining lidar wind measurements from space.

SECTION 8

RECOMMENDATIONS

From the Workshop discussions a number of recommendations were made to advance the use of wind measurements and to further the development of the wind sensing technology. These have been discussed in some detail in the previous sections and are summarized below.

8.1 METEOROLOGICAL USES OF WIND MEASUREMENTS

A variety of meteorological uses for wind data were discussed by the Workshop participants and the following recommendations emerged from these discussions: *For the global and synoptic scales:*

1. The coverage of the present global operational observing system for measuring winds should be increased over the oceans and in the tropics and in the southern hemisphere.
2. A horizontal resolution of about 100 km, vertical resolution of about 1 km ($\sim$ 0.5 km in the boundary layer and vicinity of the jet stream), and temporal resolution of 6 h are needed.
3. The accuracy of the horizontal wind components should be on the order of 1 to 2 m s^{-1} in the lower troposphere and 2 to 5 m s^{-1} in the upper troposphere, in order to make the observing system over the oceans as useful as the rawinsonde network over land.
4. Wind profiles should be measured rather than single-level data for use in numerical analysis and forecasting, because the profile data can be utilized more effectively. Also, recent simulation studies indicate that more accurate forecasts would result from using additional wind profiles compared to those obtained with additional single-level winds.

For the mesoscale, it is recommended that:

5. Satellite-borne remote sensing platforms should be used to obtain 100 km horizontal resolution soundings of wind, temperature and moisture coincident in time and space. For temperature and moisture, satellite-based platforms should be used to obtain $\sim$ 10 km resolution soundings for a variety of mesoscale events.
6. Accuracies should be on the order of 1 m s^{-1} for the horizontal wind components and 1 K for temperature and dew point.
7. Ground-based systems should be used to fulfill high-resolution observational requirements for meso-β and meso-γ phenomena (see Table 2.2).

Observing System Simulation Experiments (OSSEs) are particularly useful for quantitatively assessing the potential usefulness of proposed observing systems for global and mesoscale numerical weather prediction, local weather forecasting and diagnostic studies of atmospheric phenomena on a variety of scales. The OSSEs conducted to date indicate a very significant potential for a space-based wind profiler system. However, these studies should be expanded in a number of ways. Further work is needed to increase the realism of simulating the future global observing systems, refine data requirements, determine the effect of im-

PRECEDING PAGE BLANK NOT FILMED

PAGE 40 INTENTIONALLY BLANK

proved utilization of current and advanced temperature sounders in relation to a wind profiler, and evaluate the effect of more realistic wind profile observations. This includes the effect of correlated errors, coverage, resolution and accuracy. Coordination between GCM modelers and satellite Doppler wind profiler developers should be undertaken to improve satellite wind profiler simulations by including in the simulation experiments:

1. A statistical parameterization of the scanning errors based on mesoscale simulations, and
2. A statistical parameterization of the global aerosol distribution to account for its effect on the Doppler lidar signal-to-noise ratio and associated wind field errors.

It is also recommended that:

3. An additional model integration ("nature") be generated by ECMWF which would provide an additional record of the "true" state of the atmosphere, in order to increase the sample size for the OSSEs. Analysis/forecast experiments should also be conducted using more than one model if possible.

For the mesoscale, physical parameterizations and objective analysis and initialization methods must continue to be improved. A considerable research effort is required to develop mesoscale simulation methodology. Following the development of such methodology the effect of alternative wind observing systems should be evaluated. The assessment should include stability indices and precipitation.

8.2 WIND SENSING TECHNIQUES

The status of the various wind sensing techniques was reviewed for those instruments which are currently operational as well as those which might be deployed in space in the future.

For the operational systems, much of the discussion focused on how to improve the quality, coverage, and utilization of the cloud-motion winds (CMWs). Further research and development is recommended in the following areas:

1. The height measurement of clouds could be improved by:
   - (a) Implementing stereo cloud-top height (and perhaps cloud-base) determination via simultaneous imagery from two geosynchronous satellites.
   - (b) Implementing multispectral infrared techniques from VAS data to measure cloud-top heights.
   - (c) Increasing the utilization of surface data and thermodynamic calculations to estimate cloud-base heights in the lower troposphere.
2. Provide sufficiently high frequency geosynchronous satellite imagery (e.g., 3 min image interval) to calculate mesoscale wind fields several times a day.
3. Continue to use CMWs in tropical/subtropical environments. However, when the cloud height uncertainty is greater than 50 mb, then the vertical wind shear should be required to be less than ~ 4 m s^{-1} km^{-1} for suitable accuracy to be achieved. Also, the cloud emissivities should be high enough that height uncertainties do not introduce unacceptable errors. The use of the estimated shear could also be initiated, in conjunction with estimates of height measurement errors, to assign expected error bounds to CMW data in operational settings.

4. Conduct *in situ* verification of CMW estimates to determine actual representativeness of these estimated in continental, vertically sheared situations. Measurements made from ground-based wind profilers and aircraft equipped with inertial navigation systems, such as those which could become available in upcoming mesoscale experiments like GALE and STORM, could be used for these purposes. There is also a great potential for the use of satellite lidar data in such verification studies. There is a crucial need to know whether cloud-base levels are the most representative levels for CMW level assignment, and what cloud sizes and types are the best tracers of air motion.

5. Once the CMW heights are determined, the entire set of vectors must still be assigned to a coordinate surface before the data can be utilized in either diagnostic studies or for model initialization. Even if heights could be perfectly measured, the assignment step could still introduce significant errors > 5 m s^{-1}. This problem could be alleviated by the following:

   (a) *A priori* knowledge of the vertical wind shear profile (either from a mesoscale model forecast or some instrument like the profiler) should improve the accuracy of the interpolation of the CMWs from their actual levels to the coordinate surface.

   (b) In the absence of (a), an arbitrary assignment of CMWs to a sigma (σ) surface should reduce the magnitude of the vector differences between combined (rawinsonde and CMW) winds and rawinsonde winds, unless a moisture discontinuity is crossed, in which case,

   (c) The use of multiple σ surfaces representative of the different air masses is also recommended.

In order to develop the capability to properly utilize CMW mesoscale fields, major operational centers like NMC, NSSFC, and PROFS should be encouraged to participate in addressing the following topics:

6. Objective analysis techniques should be tailored to the specific characteristics of CMW data, namely, their highly non-uniform coverage and their (presently inadequately understood) unique statistical structure. Existing CMW data sets are adequate for this research, particularly those collected during SESAME.

7. Mesoscale model sensitivity studies need to be conducted to determine the utility of cloud-motion wind data, since such data have not yet been shown to produce sustained impacts in model forecasts.

8. Techniques need to be developed to allow CMW data to be merged or synthesized with other mesoscale data such as from PAM, wind profilers, Doppler lidar, etc.

The instruments with potential for deployment in space were reviewed in terms of: (1) the possible areas of application, (2) the present status in the development of the technique and the hardware components, and (3) the expected resolution, measurement accuracy, and coverage.

From the material presented it is recommended that:

1. Ground-based and airborne measurements by CO_2 Doppler systems be continued.

2. Ground-based wind measurements be demonstrated with incoherent Doppler lidars, and at other wavelengths for coherent Doppler lidars.

3. Advanced lidars be developed in order to obtain global aerosol backscatter measurements (0.35 μm to 11 μm).

4. Contingent on successful ground-based demonstrations, detailed feasibility studies, similar to the CO_2 studies, be conducted for the incoherent Doppler lidar and the coherent Doppler lidars at other wavelengths.
5. Development of passive sensors to measure stratospheric winds be continued.
6. The suggested improvements for obtaining better cloud-track winds should be implemented.
7. The existing Seasat data should be exploited further to improve scatterometer accuracy by: (1) developing an improved model function (backscatter-to-wind transfer algorithm), (2) incorporating environmental parameters (e.g., sea surface temperature, moisture and heat fluxes, etc.) into a physically based model function, and (3) developing improved alias removal techniques.
8. Further work be done to sharpen the user requirements for wind measurements.

Specifically related to Doppler lidar sensor development, the following recommendations are made:

9. The global aerosols should be measured to confirm adequate aerosol backscatter to support Doppler lidar measurements from space.
10. The lag-angle compensation for both coarse and fine control of the beam-pointing should be demonstrated (can best be done in a spaceborne test).
11. A spaceborne Doppler lidar wind measurement system should be demonstrated.
12. The onboard Doppler lidar data processing and transmission should be demonstrated to verify algorithm suitability (from either aircraft or space).
13. A Doppler lidar system with a compact, efficient 6 to 10 J laser should be built and flown on an aircraft.
14. To accomplish these demonstrations, and upon further verification of the required global aerosol distribution, a vigorous program for the construction and test of the necessary ground-based, aircraft-borne, and spaceborne lidars is recommended, starting in FY86 and completed by the early 1990s, leading to the construction of a wind-sensing system for Eos.

8.3 ATMOSPHERIC AEROSOLS

The importance of aerosols and other tracers for measuring winds from space was also emphasized. The discussion focused primarily on the aerosol requirements of Doppler lidar wind observing systems. Further research and development is recommended in order to:

1. Use lidar, *in situ* measurements, and remote optical techniques to improve the characterization of the free tropospheric and lower stratospheric aerosols on a global scale.
2. Understand the effects of aerosol/wind speed correlation on the radial wind measurements, determine optimum shot density and distributions to achieve accuracy objectives, and develop criteria for identifying the areas and situations when reliable Doppler lidar winds can be expected because of the unique form of the wind information yielded by Doppler lidars (both coherent and incoherent). This basis should include the global aerosol distribution and cloud-free line-of-sight statistics.

3. Use the existing and ongoing tropospheric data sets from SAGE II and the Mauna Loa Observatory to improve the global climatology of the free tropospheric aerosols.
4. Use satellite imaging to investigate the distribution of aerosol plumes over the oceans.
5. Establish a network of ground-based cross-calibrated pulsed lidars to make coordinated measurements of aerosol backscatter and to establish local backscatter climatologies at CO_2 laser wavelengths. This should include one or more stations in the southern hemisphere.
6. Establish improved calibration techniques for visible and near IR lidar systems to allow quantitative aerosol backscatter measurements to be made in "clean" air masses.
7. Initiate a coordinated global-scale aerosol backscatter measurement program. This program should include airborne over-flights of all ground or ship stations as well as special missions to provide backscatter measurements over a wide range of spatial scales.
8. Use any future shuttle-based lidar missions to measure backscatter cross-sections on a global scale.
9. Expand the high altitude aerosol laboratory at Mauna Loa to include simultaneous CO_2 lidar backscatter measurements and *in situ* measurements of aerosol microphysical and chemical properties.
10. Develop a global scale aerosol model that describes the spatial and temporal distribution of aerosol backscatter and the spectral variability from the ultraviolet to the middle infrared.
11. Investigate special geophysical events, such as volcanic eruptions, as they illustrate the extent to which aerosols are transported and modified.
12. Attempt to improve the understanding of the probability distribution of cloud sizes for various cloud types, and geographical regions using aircraft visible imaging and lidar measurements. Percentage penetration estimates should also be obtained over regions with various types of partial cloud cover using airborne lidar.

In addition to the wide range of civilian research and development activities which were discussed, discussions were also held with representatives of the United States Air Force (USAF) regarding their research and development plans in wind sensing technology.

Recommendations from USAF include:

1. Conducting simulation studies with numerical weather prediction models to test the accuracy of weather analyses and forecasts when only satellite observations are used; the simulations should include cases in which the conventional data are denied over relatively small regions as well as cases in which large areas of the globe have access only to satellite data;
2. Fabricating a ground "brass-board" lidar wind measurement system in order to reduce the uncertainty in the assumptions which are made when scaling the lidar to a space platform;
3. Intensifying the development of space-based lidar data processing techniques and establishing trade-offs between onboard and ground-based processing;
4. Defining the critical subsystems and/or components for a space-based lidar wind measurement system, initiating a critical component development program, and identifying tests which can be implemented to evaluate the critical components; and

5. Expanding the inter-disciplinary and inter-agency cooperation in an effort to accelerate the technological advances which are required for obtaining lidar wind measurements from space.

SECTION 9

REFERENCES

Arnold, C., C. Dey, and W. Bostleman, 1985: Results of an observing system simulation experiment based on the proposed Windsat instrument. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Alaka, M. A., and F. Lewis, 1967: Numerical experiments leading to the design of optimum global meteorological networks. Technical Memorandum WBTM TDL-7, Environmental Satellite Services Administration, Weather Bureau, Washington, DC.

Atlas, R., E. Kalnay, W. E. Baker, J. Susskind, D. Reuter and M. Halem, 1985: Simulation studies of the impact of future observing systems on weather prediction. *Proceedings of the Seventh Conference on Numerical Weather Prediction.* Montreal, 17–20 June, 145–151.

Baker, W. E., R. Atlas, E. Kalnay, M. Halem, P. M. Woiceshyn, S. Peteherych, and D. Edelmann, 1984: Large-scale analysis and forecast experiments with wind data from the Seasat A scatterometer, *J. Geophys. Res., 89,* 4927–4936.

Baker, W. E., and J. Paegle, 1983: The influence of the tropics on the prediction of ultralong waves. *Mon. Wea. Rev., 111,* 1341–1355.

Bengtsson, L., and N. Gustavsson, 1972: Assimilation of non-synoptic observations. *Tellus, 24,* 383–398.

Bergman, K. H., 1979: Multivariate analysis of temperatures and winds using optimum interpolation. *Mon. Wea. Rev., 107,* 1423–1444.

Best, W. H., 1955: Differences in numerical prognoses resulting from differences in analyses. *Tellus, 7,* 351–356.

Brill, K. F., L. W. Uccellini, R. P. Burkhart, T. T. Warner, and R. A. Anthes, 1985: Numerical simulations of a transverse indirect circulation and low-level jet in the exit region of an upper-level jet. *Mon. Wea. Rev., 42,* 1306–1320.

Bristor, C. L., 1958: Effect of data coverage on the accuracy of 500 mb forecasts. *Mon. Wea. Rev., 86,* 299–308.

Bromley, R. A., 1978: Simulation experiments to assess the effectiveness of the observation system for FGGE. GARP Working Group on Numerical Experimentation, Report No. 16, 1–54.

Cahir, J. J., 1971: Implications of circulations in the vicinity of jet streaks at subsynoptic scales. Ph.D. Thesis, Pennsylvania State University, 170 p.

Charney, J., M. Halem, and R. Jastrow 1969: Use of incomplete data to infer the present state of the atmosphere. *J. Atmos. Sci., 26,* 1160–1163.

Daley, R., 1980: On the optimal specification of the initial state for deterministic forecasting. *Mon. Wea. Rev., 108,* 1719–1735.

Dey, C., C. P. Arnold, and W. Bostelman, 1985: Design of a Windsat observing system simulation experiment. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Duffy, D., R. Atlas, T. Rosmond, E. Barker, and R. Rosenberg, 1984: The impact of Seasat scatterometer winds on the Navy's operational model, *J. Geophys. Res., 89,* 7238–7244.

Ebersole, K. A., 1984: Diagnostic verification of the GLAS general circulation model as applied to a case of extra-tropical maritime explosive cyclogenesis, Master's Thesis, Naval Postgraduate School, Monterey, California, 112 pp.

Federal Coordinator for Meteorological Services and Supporting Research, 1982: Review of federal research and data collection programs for improving topical cyclone forecasting. US Dept. of Commerce NOAA Report FCM-R2-1982.

Fitzjarrald, D., R. Beranek, J. Bilbro, and J. Mabry, 1985: Preliminary plan for a shuttle coherent atmospheric lidar experiment. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Fleming, R. J., T. M. Kaneshige, and W. E. McGovern, 1979a: The Global Weather Experiment 1. The observational phase through the first special observing period. *Bull. Amer. Meteor. Soc., 60,* 649-659.

__________, 1979b: The Global Weather Experiment II. The second special observing period. *Bull. Amer. Meteor. Soc., 60,* 1316-1322.

Gordon, C. T., L. Umscheid, and K. Miyakoda, 1972: Simulation experiments for determining wind data requirements in the tropics. *J. Atmos. Sci., 29,* 1064-1075.

Gurk, H. M., P. G. Kaskiewicz, W. P. Altman, 1985: Windsat free flyer using the advanced TIROS-N satellite. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Halem, M., and R. Jastrow, 1970: Analysis of GARP data Requirements. *J. Atmos. Sci., 27,* 177.

Halem, M., E. Kalnay-Rivas, W. E. Baker, and R. Atlas, 1982: An assessment of the FGGE satellite observing system during SOP-1. *Bull. Amer. Meteor. Soc., 63,* 407-426.

Hall, F. F., R. M. Huffaker, R. M. Hardesty, M. E. Jackson, T. R. Lawrence, M. J. Post., R. A. Richter, and B. F. Weber, 1984: Wind measurement accuracy of the NOAA pulsed infrared Doppler lidar. *Appl. Opt., 23,* 2503-2506.

Hasler, A. F., W. C. Skillman, and W. E. Shenk, 1979: In situ aircraft verification of the quality of satellite cloud winds over oceanic regions. *J. Appl. Meteor., 18,* 1481-1489.

Huffaker, R. M., 1978: Feasibility study of satellite-borne lidar global wind monitoring system. NOAA Tech. Memo. ERL WPL-37, 297 pp.

Huffaker, R. M., T. R. Lawrence, R. J. Keller, M. J. Post, J. T. Priestly, and J. A. Korrell, 1980: Feasibility study of a satellite-borne lidar global wind monitoring system, Part II. NOAA Tech. Memo. ERL WPL-63, 124 pp.

Jastrow, R., and M. Halem, 1970: Simulation studies related to GARP. *Bull. Amer. Meteor. Soc., 51,* 490-513.

Jess, E. O., 1959: A numerical prediction experiment involving data paucity and random errors. *Tellus, 12,* 21-30.

Jones, W. L., L. C. Schroeder, D. H. Boggs, E. M. Bracalente, R. A. Brown G. J. Dome, W. J. Pierson, and F. J. Wentz, 1982: The Seasat A satellite scatterometer: The geophysical evaluation of remotely sensed wind vectors over the ocean. *J. Geophys. Res., 81,* 3297-3317.

Kallberg, P., S. Uppala, R. Pasch, S. Tibaldi, 1985: Progress report on FGGE reanalysis. Global Weather Experiment Newsletter, No. 12, National Academy of Sciences, 1-6.

Kalnay, E., J. C. Jusem, and J. Pfaendtner, 1985: The relative importance of mass and wind data in the present observing system. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Kasahara, A., and D. Williamson, 1972: Evaluation of tropical wind and reference pressure measurements: Numerical experiments for observing systems. *Tellus, 24,* 100-115.

Krishnamurti, T. N., N. Surgi, and J. Manobianco, 1984: Recent results on divergent circulations over the global tropics. Florida State University Report No. 84-1, 20 pp.

Kuo, Y.-H. and R. A. Anthes, 1985: Calculation of geopotential and temperature fields from an array of nearly continuous wind observations. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Lally, V. E., 1985: Reference level winds from balloon platforms. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Lockheed Missiles and Space Company, 1981: Global wind measuring satellite system—Windsat. Final Report LMSC-D767868, prepared for NOAA/WPL under contract NA79RSC00127.

Lorenc, A. C., 1975: Results of observing systems simulation experiments for the First GARP Global Experiment. GARP Working Group on Numerical Experimentation, Report No. 10, 37–68.

Maddox, R. A., A. J. Negri, and T. H. VonderHaar, 1977: Analysis of satellite-derived winds for April 22, 1975. Preprints 10th Conf. on Severe Local Storms, American Meteorological Society Omaha, Nebraska, 10–18 October 54–50.

Menzies, R. T., and M. J. Kavaya, 1985: Coherent CO_2 lidar measurements of aerosol backscatter coefficients: Wavelength dependence in the 9–11 μm region. Coherent Laser Radar: Technology and Applications, Great Malvern England, 7-11 July, Aldine Press Ltd., Great Malvern, 181–184.

National Environmental Satellite, Data and Information Service, 1985: NOAA satellite requirements forecast, U.S. Dept. of Commerce NOAA Envirosat-2000 Report, 113 pp.

Negri, A. J. and T. H. Vonder Haar, 1980: Moisture convergence using satellite-derived wind fields: A severe local storm case study. *Mon. Wea. Rev., 108,* 1170–1182.

Newton, C. W., 1954: Analysis and data problems in relation to numerical prediction. *Bull. Amer. Meteor. Soc., 35,* No. 7, 287–294.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc., 56,* 527–530.

Peslen, C. A., 1980: Short-interval SMS wind vector determinations for a severe local storm area. *Mon. Wea. Rev., 107,* 1407–1418.

Peslen, C. A., S. E. Koch, and L. W. Uccellini, 1985: The effect of the arbitrary level assignment of satellite cloud motion wind vectors on wind analyses in the pre-thunderstorm environment. NASA Tech. Memo. 86186., 56 pp.

Phillips, N. A., 1983: An accuracy goal for a comprehensive satellite wind measuring system. *Mon. Wea. Rev., 111,* 237–239.

Post, M. J., 1985: Atmospheric infrared backscattering profiles: Interpretation of statistical and temporal properties. NOAA Tech. Memo. ERL WPL-122; Boulder, Colorado, 105 pp.

Rees, D., 1985: Balloon-based interferometric techniques. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Roberts, R. D. and J. McCarthy, 1985: Severe wind flow of small spatial and temporal scales: the microburst and related phenomena. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Rossby, C. G., 1938: On the mutual adjustment of pressure and velocity distribution in certain simple current systems. *J. Marine Research, 1,* 239-263.

Schlatter, T. W., 1985: Use of ground-based wind profiles in mesoscale forecasting. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Schroeder, L. C., D. H. Boggs, G. J. Dome, I. M. Halberstam, W. L. Jones, W. J. Pierson and F. J. Wentz, 1982: The relationship between wind vector and normalized radar cross section used to derive Seasat A satellite scatterometer winds. *J. Geophys. Res., 87,* 3318–3336.

Shenk, W. E., R. F. Adler, D. Chester, J. Susskind, and L. Uccellini, 1985: The rational and suggested approaches for research geosynchoronous satellite measurements for severe storm and mesoscale investigations. NASA Tech. Memo. 86185, 29 pp.

Skinner, W. R., P. B. Hays, and V. J. Abreu, 1985: Wind measurements with a high resolution Doppler imager (HRDI). *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

Snow, J. W., J. T. Bunting, R. P. d'Entremont, D. D. Grantham, K. R. Hardy, and E. M. Tomlinson, 1985: Space Shuttle cloud photographs assist in correcting meteorological satellite data. *EOS, 66,* 489–490.

Spencer, N. W., L. E. Waharton, H. B. Neimann, A. E. Hedin, G. R. Carignan, and J. C. Maurer, 1981: The Dynamic Explorer wind and temperature spectrometer. *Space Sci. Instrum, 5,* 417–428.

Stewart, T. R., and C. M. Hayden, 1985: A FGGE water vapor wind dataset. *Proceedings of the NASA Symposium on Global Wind Measurements,* A. Deepak Publishing, Hampton, Virginia.

The National STORM Program, 1984: STORM-central phase, preliminary program design. Prepared by NCAR and the Interagency Team for STORM-Central, 147 pp.

Washington, W., 1964: A note on the adjustment towards geostrophic equilibrium in a simple fluid system. *Tellus, 16,* 530–534.

Williamson, D. L., 1973: The effects of forecast error accumulation on four-dimensional data assimilation. *J. Atmos. Sci., 30,* 537–543.

Williamson, D. L., 1981: Storm track representation and verification. *Tellus, 33,* 513–530.

Williamson, D. L., and A. Kasahara, 1971: Adaption of meteorological variables forced by updating. *J. Atmos. Sci., 28,* 1313–1324.

Woiceshyn, P. M., M. G. Wurtele, D. H. Boggs, L. F. McGoldrick, and S. Peteherych, 1986: The necessity for a new parameterization of an empirical model for wind/ocean scatterometry. *J. Geophys. Res., 91,* in press.

APPENDIX A

TECHNICAL PROGRAM

of the

SYMPOSIUM AND WORKSHOP ON GLOBAL WIND MEASUREMENTS

29 July–1August 1985 — Columbia Inn, Columbia, Maryland

SUNDAY EVENING, 28 July 1985

6:00 - 8:00 REGISTRATION and RECEPTION

MONDAY, 29 July 1985

8:30 am Welcoming Remarks
Robert J. Curran, NASA Headquarters
Wayman E. Baker, NASA/GSFC

PLENARY SESSION I
METEOROLOGICAL USES OF WIND MEASUREMENTS

I-A: Atmospheric Scales of Motion
Chairman: **William D. Bonner,** NOAA/NMC/NWS

8:40		Introduction and Overview *William D. Bonner,* NOAA/NMC/NWS
8:50	I-A.1	The Relative Importance of Mass and Wind Data in the Current Global Observing System *Eugenia Kalnay,* NASA/GSFC
9:10	I-A.2	The Analysis and Forecast Sensitivity to Tropical Wind Data *Jan Paegle,* University of Utah
9:30	I-A.3	Tropical Upper Tropospheric Motion Field *T.N. Krishnamurti,* Florida State University
9:50		REFRESHMENT BREAK
10:10	I-A.4	Observation Requirements for the Regional Scale *Louis W. Uccellini,* NASA/GSFC
10:30	I-A.5	The NMC Regional Analysis System *Geoffrey I. DiMego,* NOAA/NMC
10:50	I-A.6	The Impact of Mesoscale Data on the Simulation of a Mesoscale Convective Weather System *J. Michael Fritsch,* Penn State University
11:10	I-A.7	DOD Operational Applications of Wind Measurements *Allan C. Ramsay,* OUSDRE

11:30	I-A.8	Use of Ground-Based Wind Profiles in Mesoscale Forecasting ***Thomas W. Schlatter,*** NOAA/ERL
11:50	I-A.9	Severe Wind Flows of Small Spatial and Temporal Scales: The Microburst and Related Phenomena ***Rita D. Roberts*** and John McCarthy, NCAR
12:10	pm	LUNCH
1:30	I-A.10	Mesoscale Applications of Cloud-Track Winds in a Baroclinic Atmosphere ***Steven E. Koch,*** NASA/GSFC
		I-B: Observing System Simulation Experiments Chairman: **Robert M. Atlas,** NASA/GSFC
1:50	I-B.1	Observing System Simulation Experiments at GSFC ***Robert M. Atlas,*** NASA/GSFC
2:10	I-B.2	Design of a Windsat Observing System Simulation Experiment ***Clifford H. Dey*** and Charles P. Arnold, Jr., NOAA/NMC
2:30	I-B.3	Results of an Observing System Simulation Experiment Based on the Proposed Windsat Instrument ***Charles P. Arnold, Jr.*** and Clifford H. Dey, NOAA/NMC
2:50		REFRESHMENT BREAK
3:10	I-B.4	Use of Wind Data in Global Modeling ***Jean Pailleux***, ECMWF
3:30	I-B.5	Calculation of Geopotential and Temperature Fields from an Array of Nearly Continuous Wind Observations ***Ying-Hwa Kuo*** and Richard Anthes, NCAR
3:50 - 5:00		Planning Meeting for Workshop Participants
5:30		ICEBREAKER

TUESDAY, 30 July 1985

PLENARY SESSION II
WIND SENSING TECHNIQUES

8:30	am	Introduction and Overview ***James W. Bilbro***, NASA/MSFC
		II-A: Operational Wind Sensing Techniques Chairman: **Fred Brock**, University of Hawaii
8:35		Introduction ***Fred Brock***, University of Hawaii
8:50	II-A.1	Balloon Probing Techniques James Arnold, NASA/MSFC

9:10	II-A.2	Reference Level Winds from Balloon Platforms ***Vincent E. Lally***, NCAR
9:30	II-A.3	Balloon-Based Interferometric Techniques ***David Rees***, University College of London
9:50	II-A.4	Aircraft/ASDAR ***James K. Sparkman, Jr.***, NOAA
10:10		REFRESHMENT BREAK
10:30	II-A.5	Cloud and Water Vapor Wind Measurements from Geostationary Satellites ***Tod Stewart,*** William L. Smith, and W.P. Menzel, University of Wisconsin
10:50	II-A.6	Improving the Quality, Coverage, and Utilization of Cloud Motion Derived Winds ***William E. Shenk***, NASA/GSFC
11:10	II-A.7	Interferometric Winds ***W.R. Skinner***, University of Michigan
11:30	II-A.8	Inferred Winds ***John H. Ward***, NOAA/NMC
11:50		LUNCH

II-B: Potential Space-Borne Techniques

Chairman: **Milton Huffaker**, Coherent Technologies, Inc.

1:10		Introduction and Overview ***Milton Huffaker***, Coherent Technologies, Inc.
1:20	II-B.1	Doppler Radar Wind Profilers ***Richard G. Strauch***, NOAA/ERL
1:40	II-B.2	Gas Correlation Remote Sensing of Stratospheric and Mesospheric Wind ***Daniel J. McCleese***, and Jack S. Margolis, Jet Propulsion Laboratory
2:00	II-B.3	Satellite Scatterometers for Oceanic Surface Wind Measurements ***M.H. Freilich,*** F.K. Li, P.S. Callahan, and C. Winn, Jet Propulsion Laboratory
2:20	II-B.4	Incoherent, Excimer Laser Based, Doppler Lidar System ***I. Stuart McDermid,*** J.B. Laudenslager, and D. Rees, Jet Propulsion Laboratory
2:40	II-B.5	Development of a 0.5 μm Incoherent Doppler Lidar for Space Application ***Ari Rosenberg*** and Jeff Sroga, RCA Astro Electronics
3:00		REFRESHMENT BREAK

3:20	II-B.6	Aerosol Pattern Correlation ***Ed Eloranta***, University of Wisconsin
3:40	II-B.7	Coherent Doppler Lidar-Current US 9–11 μm Systems ***Freeman F. Hall***, NOAA/WPL
4:00	II-B.8	Current European Systems ***Michael Vaughan***, Royal Signals and Radar Establishment
4:20	II-B.9	1.06 μm Systems ***Robert Byer***, Stanford University
4:40	II-B.10	A Discussion of the Effects of Wavelength on Coherent Doppler Lidar Performance ***T.R. Lawrence***, NOAA/WPL
5:00	II-B.11	Comparison of Coherent and Incoherent Doppler Lidar Systems ***Robert T. Menzies***, Jet Propulsion Laboratory
7:00 - 9:00		POOLSIDE BARBECUE

WEDNESDAY, 31 July 1985

II-B: Potential Space-Borne Techniques (Continued)

8:30	II-B.12	Lockheed Windsat Study ***Steve Martin***, Lockheed Missile & Space Co., Inc.
8:50	II-B.13	Windsat Free-Flyer Using the Advanced TIROS-N Satellite ***Herbert M. Gurk,*** Paul F. Kaskiewiez and Wolf P. Altman, RCA Astro Electronics
9:10	II-B.14	Shuttle Demonstration Study ***D. Fitzjarrald***, NASA/MSFC

PLENARY SESSION III
MEASUREMENT SIMULATION STUDIES
Chairman: **Freeman F. Hall**, NOAA/ERL

9:35		Introduction ***Freeman F. Hall***, NOAA/ERL
9:40	III.1	Global Sampling Strategies and Accuracies ***R. Milton Huffaker***, Coherent Technologies, Inc.
10:00		REFRESHMENT BREAK
10:20	III.2	Doppler Lidar Sampling Strategies and Accuracies-Regional Scale ***G. David Emmitt***, Simpson Weather Associates, Inc.
10:40	III.3	Cloud Obscurations and Statistics ***W. Snow***, Air Force Geophysics Lab
11:00	III.4	Distribution of Atmospheric Aerosols and CO_2 Lidar Backscatter Simulation ***G.S. Kent,*** U. Farrukh, P. Wang and A. Deepak, Science and Technology Corp.

11:20	III.5	Aerosol Sampling Strategies for a Global Aerosol Model ***David A. Bowdle***, NASA/MSFC
11:40	III.6	Global Aerosol Distribution Walter Frost and **Gary G. Worley**, FWG Associates, Inc.
12:00	pm	LUNCH
1:00 - 5:00		Working Groups Prepare Recommendations and Draft Workshop Report

SPECIAL SESSION:
AIR FORCE DEVELOPMENTS TOWARD SPACE WIND SENSING
Chairman: **Vince Falcone**, Air Force Geophysics Laboratory

7:30	pm	Introduction ***Vince Falcone***, Air Force Geophysics Laboratory
7:40	SS.1	DMSP Lidar Program ***Gary L. Duke*** and Richard Higgins, DMSP/Space Division
8:00	SS.2	New Avenues for Lidar Technology ***Milton Birnbaum***, New Advances for Lidar Technology
8:20	SS.3	Ground-Based Lidar Measurements of Stratospheric and Mesospheric Density and Aerosols ***D. Sipler,*** R. Philbrick, C. Bix, and M. Gardner, Air Force Geophysics Laboratory
8:40	SS.4	AFGL Mobile CO_2 Doppler Lidar ***S. Alejandro***, Air Force Geophysics Laboratory
9:00	SS.5	Backscatter Measurements from a Balloon-Borne Lidar ***D. Bedo*** and R. Swirbalus, Air Force Geophysics Laboratory

THURSDAY, 1 August 1985

PLENARY SESSION IV

8:30 - 12:00	Amend Report and Finalize Recommendations of Working Groups
12:00	ADJOURN

APPENDIX B

LIST OF PARTICIPANTS

Donald T. Acheson
NOAA National Weather Service

S. Alejandro
Air Force Geophysics Laboratory

Frank Allario
NASA Langley Research Center

Charles Arnold
NOAA National Meteorological Center

David Atlas
University of Maryland

Robert M. Atlas
NASA Goddard Space Flight Center

Clayton Bair
NASA Langley Research Center

Wayman E. Baker
NASA Goddard Space Flight Center

William R. Bandeen
NASA Goddard Space Flight Center

Donald E. Bedo
Air Force Geophysics Laboratory

Chandrakant Bhumralkar
NOAA Headquarters

James W. Bilbro
NASA Marshall Space Flight Center

Milton Birnbaum
The Aerospace Corporation

Stephen C. Bloom
NASA Goddard Space Flight Center

Reinout Boers
NASA Goddard Space Flight Center

William D. Bonner
NOAA National Meteorological Center

David A. Bowdle
NASA Marshall Space Flight Center

Charles M. Bradford
Ball Aerospace

Genia Brin
NASA Goddard Space Flight Center

Fred Brock
University of Oklahoma

John A. Brown
NOAA National Meteorological Center

Robert Byer
Stanford University

Robert Center
Spectra Technology, Inc.

Robert J. Curran
NASA Headquarters

Adarsh Deepak
Science and Technology Corporation

A. J. Desmarais
NOAA National Meteorological Center

Clifford H. Dey
NOAA National Meteorological Center

Geoffrey J. DiMego
NOAA National Meteorological Center

James C. Dodge
NASA Headquarters

Stanley Doore
OFCM

Gary L. Duke
DOD/United States Air Force

Ed Eloranta
University of Wisconsin

G. David Emmitt
Simpson Weather Associates

David Escoe
Aerospace Corporation

Vince Falcone
Air Force Geophysics Laboratory

George Fichtl
NASA Marshall Space Flight Center

Dan Fitzjarrald
NASA Marshall Space Flight Center

Pierre H. Flamant
Laboratoire de Meteorologie Dynamique

[redacted]

Michael H. Freilich
NASA Jet Propulsion Laboratory

Michael J. Fritsch
Pennsylvania State University

Walter Frost
FWG Associates, Inc.

Herbert M. Gurk
RCA Astro Electronics

Freeman Hall
NOAA Wave Propagation Laboratory

Kenneth R. Hardy
Air Force Geophysics Laboratory

Edward J. Harrison
Department of Defense

M. Helfand
NASA Goddard Space Flight Center

Robert V. Hess
NASA Langley Research Center

Richard Higgins
DOD Defense Meteorological
Satellite Program

Milton Huffaker
Coherent Technologies, Inc.

George Hughes
NOAA National Environmental
Satellite, Data and Information Service

Karl R. Johannessen
Science and Technology Corporation

David F. Jones
University of Maryland

Eugenia Kalnay
NASA Goddard Space Flight Center

Thomas Kaneshige
World Meteorological Organization

Michael J. Kavaya
NASA Jet Propulsion Laboratory

Geoffrey Kent
Science and Technology Corporation

James L. Kinter
University of Maryland

S. Koch
NASA Goddard Space Flight Center

T. N. Krishnamurti
Florida State University

William Kuo
National Center for
Atmospheric Research

Vincent Lally
National Center for
Atmospheric Research

James B. Laudenslager
NASA Jet Propulsion Laboratory

Rhidian Lawrence
NOAA Wave Propagation Laboratory

Jack S. Margolis
NASA Jet Propulsion Laboratory

Stephen C. Martin
Lockheed Missile Company

M. Patrick McCormick
NASA Langley Research Center

I. Stuart McDermid
NASA Jet Propulsion Laboratory

S. H. Melfi
NASA Goddard Space Flight Center

Robert Menzies
NASA Jet Propulsion Laboratory

Richard R. Nelms
NASA Langley Research Center

Jan Paegle
University of Utah

Jean Pailleaux
European Center for Medium
Range Weather Forecasts

Cynthia Peslen
NASA Goddard Space Flight Center

Russell Philbrick
Air Force Geophysics Laboratory

Allan C. Ramsay
Department of Defense

David Rees
University College of London

Dennis Reuter
NASA Goddard Space Flight Center

Richard Reynolds
NOAA National Meteorological Center

David M. Rider
NASA Jet Propulsion Laboratory

Rita D. Roberts
National Center for
Atmospheric Research

William F. Roberts
National Center for
Atmospheric Research

Leonard Robinson
LMSC

Edward Rodgers
NASA Goddard Space Flight Center

Richard D. Rosen
Atmospheric and
Environmental Research

Ari Rosenberg
RCA Astro Electronics

H. Rosenwasser
Science and Technology Corporation

David Salstein
Atmospheric and
Environmental Research

Robert Schiffer
NASA Headquarters

Tom Schlatter
NOAA Environmental
Research Laboratories

Siegfried Schubert
NASA Goddard Space Flight Center

Anne Seigel
NOAA National Meteorological Center

William E. Shenk
NASA Goddard Space Flight Center

Joanne Simpson
NASA Goddard Space Flight Center

Wilbert Skinner
University of Michigan

J. W. Snow
Air Force Geophysics Laboratory

Richard C. J. Somerville
Scripps Institution of Oceanography

James K. Sparkman
NOAA National Environmental Satellite,
Data and Information Service

Jeff Sroga
RCA Astro Electronics

Tod R. Stewart
University of Wisconsin

Richard G. Strauch
NOAA Environmental Research
Laboratories

John Theon
NASA Headquarters

L. Uccellini
NASA Goddard Space Flight Center

Peter J. Vanderwolf
OFCM

Michael Vaughan
Royal Signals and Radar Establishment

Sastri Vemury
Science and Technology Corporation

John H. Ward
NOAA National Meteorological Center

T. D. Wilkerson
University of Maryland

Peter M. Woiceshyn
NASA Jet Propulsion Laboratory

James Austin Woods
European Centre for Medium Range
Weather Forecasts

Gary G. Worley
FWG Associates, Inc.

Man-Li Wu
NASA Goddard Space Flight Center

Chien-hsiung Yang
Air Force Geophysics Laboratory

H. Y. Michael Yeh
Systems and Applied Sciences Corporation

APPENDIX C

GLOSSARY OF ACRONYMS

AFGL	Air Force Geophysics Laboratory
ASAP	Automatic Shipboard Aerological Program
ASDAR	Aircraft to Satellite Data Relay
ATS	Applications Technology Satellite
CLASS	Cross-Chain Loran Atmospheric Sounding System
CMW	Cloud-Motion Wind
dB	decibel
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
ECMWF	European Centre for Medium Range Weather Forecasts
Eos	Earth Observing System
ERL	Environmental Research Laboratories
ERS-1	ESA Remote Sensing Satellite
ESA	European Space Agency
FGGE	First GARP Global Experiment
GALE	Genesis of Atlantic Lows Experiments
GARP	Global Atmospheric Research Program
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
GHOST	Global HOrizontal Sounding Technique
GLA	Goddard Laboratory for Atmospheres
GMCC	Geophysical Monitoring for Climatic Change
GSFC	Goddard Space Flight Center
HRDI	High Resolution Doppler Imager
JPL	Jet Propulsion Laboratory
LaRC	Langley Research Center
MCS	Mesoscale Convective System
MICRO-GHOST	Operational Successor to GHOST
MIST	Microburst, Severe Thunderstorm
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
Nd:YAG	Neodymium dopant in a host crystal of Yttrium Aluminum Garnet
NESDIS	National Environmental Satellite, Data, and Information Service
NEXRAD	Next-Generation Weather Radar
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NROSS	Navy Remote Ocean Sensing Satellite
NSSFC	National Severe Storms Forecast Center
NWP	Numerical Weather Prediction
NWS	National Weather Service
OI	Optimum Interpolation
OSSE	Observing System Simulation Experiment
OUSDRE	Office of the Undersecretary of Defense for Research and Engineering
OWSE	Operational WWW System Evaluation

PAM	Portable Automated Mesonet
PROFS	Program for Regional Observing and Forecasting Services
RADARSAT	Radar Satellite (Canadian)
RCA	Radio Corporation of America
rms	root mean square
RSRE	Royal Signals and Radar Establishment
SAGE	Stratospheric Aerosol and Gas Experiment
SAM	Stratospheric Aerosol Measurement
SAR	Synthetic Aperture Radar
SASS	Seasat A Satellite Scatterometer
SCALE	Shuttle Coherent Atmospheric Lidar Experiment
SESAME	Severe Environmental Storms and Mesoscale Experiment
SPACE	Satellite Precipitation and Cloud Experiment
SSM/I	Special Sensor Microwave/Imager
STC	Science and Technology Corporation
STORM	STormscale Operational and Research Meteorology
TEA	Transverse Excited Atmospheric
TOVS	TIROS-N Operational Vertical Sounder
UARS	Upper Atmosphere Research Satellite
UHF	Ultra High Frequency
USAF	United States Air Force
VAS	VISSR Atmospheric Sounder
VHF	Very High Frequency
VISSR	Visible Infrared Spin-Scan Radiometer
WPL	Wave Propogation Laboratory
WWW	World Weather Watch